Visual Perception of Location, Orientation and Length: An Eye-Movement Approach

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Bielefeld, 17th June 2003 Hendrik Koesling

Abstract

One of the most common tasks in life is probably that of visual object recognition and comparison. We often have to decide, for example, which of two objects is smaller, longer or, in general, more suitable for an intended use. This task might considerably be complicated when objects are quite alike, located far apart or not being visible at the same time. The comparison process is thus not only influenced by the relevant intrinsic object attributes, but also by object similarity and the objects' spatial and temporal relations to each other.

This PhD thesis documents a comprehensive investigation of the visual assessment of typical attributes of abstract stimuli in different comparison scenarios, taking similarity and relational aspects into account as well. The analysis of data recorded in eye-tracking experiments provided insight into underlying perceptive and cognitive processes during such object comparison tasks, focussing on characteristic stimulus features such as positional eccentricity, line segment length and orientation. The empirical findings then led to the implementation of corresponding computational models that can be employed in machine-vision systems.

In principle, the focal points of the investigations that are presented here were guided by the *cognitive structure* of visual comparison tasks. This structure can be characterised by the following processing steps: *Assessment, memorisation, comparison.* The validity of two fundamental hypotheses was tested in order to explore these processes in detail.

The first hypothesis addressed the *decomposition* of length and orientation assessment: Can the assessment of line segment length or orientation be accomplished by assessing the locations of the end points of a line segment and the subsequent *"fusion"* of the location data to yield line segment length or orientation? The hypothesis was investigated in a *gaze-contingent comparison* scenario with *sequential* stimulus presentation. Results demonstrated a high correlation between the assessment error of peripherally perceived lengths or orientations of line segments and the mislocation of marker positions, depending on eccentricity. The empirical data generally supports the hypothesis: The assessment of a line segment can be formalised as the localisation of line segment end points and the computation of their distance to yield line segment length. In analogy, the computation of the spatial relation of end points yields line segment orientation. An accordingly implemented, *probabilistic computational model* successfully reproduced the empirical findings and thus yielded further support for the proposed underlying perception principles.

The second hypothesis formulated the existence of *two distinct visual processing strategies* when assessing line segment length in a *free gaze, simultaneous comparison* scenario: Depending on the *discrimination difficulty*, either *holistic* or *analytic* visual processing strategies are pursued. These strategies should manifest in characteristic eye-movement patterns. Results show that the *holistic* strategy is apparently a *peripheral* process as such: Length is *mentally represented* as the distance between a fixated and a peripherally perceived end point of a line segment. In contrast, a specific pattern of *foveal visual attention* is characteristic for the *analytic* perception strategy, influenced by peripheral length perception. *Saccadic "visual measurement"* constitutes the basis for the *memorisation*

and manipulation of the corresponding mental line segment representations. If the mental representations are not sufficiently accurate to solve the given comparison task – Which of two line segments is the longer one? – assessment and mental mapping are re-iterated. The findings also helped to better understand visual phenomena such as the *horizontal-vertical illusion* which appears to be induced by inaccurate measurement at a *oculomotor* level already. Integrating components of the "eccentricity model", in particular stimulus *decomposition*, a *comprehensive computational model* could be developed. It takes into account the visual length assessment strategies and convincingly reproduces the empirical data. This yields further support for the involvement of the proposed mechanisms in the assessment of line segment attributes in the chosen comparison scenarios.

Contents

Chapter 1

Motivation

1.1 The Brain–Computer Analogy

The brain can certainly be considered one of nature's most complex structures. It must be assumed, however, that human consciousness of this complexity has only developed with the evolution of the brain itself: At some stage, humans "decided" to find out more about the brain. Ever since, attempts have been made to understand how the brain works. In the present "computer era", *comparing the brain to the computer* has been by far the most important metaphor.

Two very different insights apparently motivate the characterisation of the brain as a computer (Churchland & Grush, 1997). The first and more fundamental assumes that the defining function of nervous systems is *representational*: Brain states represent states of some other system – the outside world or the body itself – where transitions between states can be explained as computational operations on representations. The second insight is derived from a domain of mathematical theory that defines computability in a highly abstract sense. The mathematical approach is based on the idea of a Turing machine (Turing, 1950). Not an actual machine, the Turing machine is a conceptual way of saying that a well-defined function could be executed, step by step, according to simple "if-you-are-in-state-P-and-have-input-Q-then-do-R" rules, given enough time. Insofar as the brain is a device whose input and output can be characterised in terms of some mathematical function – however complicated – then in that very abstract sense, it can be mimicked by a Turing machine. Because neurobiological data indicates that brains are indeed cause-effect machines, brains are, in this formal sense, equivalent to a Turing machine as stated in the Church-Turing thesis (Church, 1936; Turing, 1936; Kleene, 1967).

Significant though this result is mathematically, it reveals nothing specific about the nature of mind-brain representation and computation. It does not even imply that the best explanation of brain function will actually be in computational/representational terms. For in this abstract sense, livers, stomachs and brains, even the solar system, all compute. What is believed to make the brain unique, however, is its evolved capacity to represent the brain's body and its world, and by virtue of computation, to *produce coherent, adaptive motor behaviour in real time*. Precisely what properties enable the brain to do this requires *empirical*, not just mathematical, investigation.

This challenging task brought together scientists from different research field, leading to the launch of a novel research discipline, namely *Cognitive Science*. Based on the idea that the *mind* is an information processing system where the *mind* is to the brain as a computer's software is to its hardware, interdisciplinary teams were established to explore the brain's processing principles. The major contributor disciplines have been psychology, computer science, biology, neuroscience, medicine, physics, linguistics as well as philosophy. However, each discipline has its own motive for this pursuit of knowledge, for example (Pomplun, 1998):

Philosophy: Are human beings "only" biological supercomputers? What is consciousness and under which circumstances can it arise?

Psychology: How do individuals gather, store and share information about themselves and their environment?

Medicine: Getting more information on the brain's functional structure will result in more patients with brain injuries or abnormalities being cured.

Computer Science: What can we learn from the brain in order to improve our "Artificial Intelligence" systems? The better we understand the way our brain works, the better human-computer interfaces can be constructed.

Along with the developments in cognitive science, new techniques were being pioneered in *neurophysiology* that allowed scientists to begin to understand the workings of the brain as an information processing device. Neurophysiologists, for example, developed methods for recording the activity of individual brain cells. This technique allowed Nobel Laureates David Hubel and Thorsten Wiesel to determine the patterns of retinal stimulation that caused cells in visual cortex to fire (Hubel & Wiesel, 1962). Several decades of work building on their pioneering studies have increased the understanding of the physiological mechanisms underlying *vision* which serves as a model for other areas of the brain. Due to its *invasive* nature, however, this method could only be tested on animals. Furthermore, higher cognitive processing, for example related to language, could not be explored.

More recent advances in physiology evolved from various brain scanning and imaging techniques, such as computer-assisted tomography (CT), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and positron emission tomography (PET). These methods display images of brain activity in a *non-invasive* manner:

EEG: Electroencephalography uses a number of electrodes (between 16 and 64) on a subjects' scalp to measure the oscillation of electric potentials caused by the activity of neurons (da Silva, 1987). EEG provides high temporal resolution (<1ms), but unsatisfactory spatial accuracy. Only the potentials in the brain's outermost layers can be measured this way, and it is not clear to what extent this data interferes with potentials in the inner brain regions.

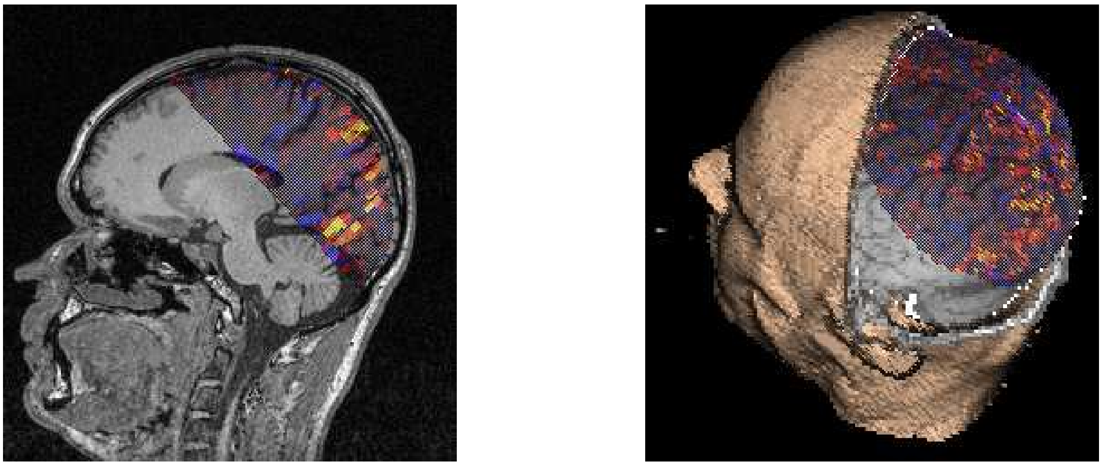


Figure 1.1: MRI (b/w) with an fMRI overlay (coloured areas). The yellow/orange regions at the back of the brain are most strongly responding to a visual stimulus.

PET: Positron emission tomography is a tracer method which uses compounds labelled with short-lived positron emitters to visualise and quantitate biochemical processes (Taylor, 1990). PET yields spatial information on brain activation in high resolution (approx. 1mm), but no accurate temporal data. Therefore, only *regions* of activation can be determined; activation dynamics are not available.

fMRI: Based on measuring nuclear magnetic resonance (Horowitz, 1995), functional magnetic resonance imaging analyses *changes* in the chemical composition of brain areas or in the flow of fluids that occur over time ("conventional" MRIs do not contain functional information, they only yield brain images). In the brain, blood perfusion is presumably related to neural activity, so fMRI, like PET, visualises the brain function when subjects perform specific tasks or are exposed to specific stimuli (Figure 1.1). However, fMRI shows better temporal and spatial resolution than PET (Cohen & Bookheimer, 1994).

MEG: Magnetoencephalography measures the electric field (outside the head), generated by the electric current that is constituted by activated ("firing") neurons (George et al., 1995). As the magnetic field is very small, extremely sensitive magnetic detectors – SQUIDs, Superconducting Quantum Interference Devices – must be used. The equipment is expensive and experiments can only take place in magnetically shielded environments (Gallen et al., 1994). MEG yields both excellent spatial and temporal data. However, as only two thirds of the cortical currents are tangential to the skull and can thus be detected by the sensors, one third of the currents remains invisible for MEG. Figure 1.2 shows the probe biomagnetometer (left) and the brain's "activation" image for a moving stimulus (right).

CT: Computer tomography uses low-ionising X- or γ-ray beams at various angles to create cross-sectional images of specific areas, providing information on the spatial distribution of mass density, atomic number and chemical species down to the micron

Figure 1.2: Left: BTi 37 channel probe biomagnetometer (Biomagnetic Technologies, USA). Right: Magnetic field over the brain, 0.15 seconds after display of a moving visual stimulus. The yellow/orange region indicates where the magnetic field is strongest.

level. The sequence of images creates a 3-dimensional representation in much greater detail than a conventional x-ray.

These non-invasive techniques have allowed *human* brains to be studied in ways heretofore impossible. For example, scientists can now identify specific regions of brain damage in neurological patients so that symptoms can be correlated with anatomical location. Using these methods in conjunction with those of cognitive psychology, cognitive neuroscientists are beginning to map out the function of major areas of the human brain and to understand how they interact – as necessary for the analysis of complex cognitive phenomena.

However, the *direct* measurement of neural activity has its limitations and presents several drawbacks. Apart from the aspects already mentioned, such as costs and bulk of equipment, the interpretation of directly measured data can be very difficult. Correspondences between patterns of neural activity and specific mental processes, especially with respect to high-level functions, are difficult to establish. Furthermore, experiments using the above-mentioned methodologies often do not provide the most naturalistic circumstances in which to study human cognition. With fMRI, for example, human participants must be almost entirely motionless while their heads are engulfed in the surprisingly loud fMRI apparatus.

Alternatively, various methods of *indirect* investigation of mental processes can be applied. Indirect methods are based on the idea that the brain "communicates" with the environment through diverse channels or "interfaces". Hence, channels that stimulate brain activity can be considered "input devices", and those that generate response "output devices". In humans, these interfaces are either uni- or bidirectional, i.e., they either serve exclusively as input or output devices or they realise both modalities. Hearing, for example, is strictly unidirectional (input), whereas haptics can be bidirectional – tactile sensoring (input) and object manipulation (output) with the hands. Employing such indirect methods, a chosen "input device" is stimulated and the corresponding reaction of a suitable "output device" is recorded. Measuring and analysing parameters of human *behaviour* in specific experimental situations then allows researchers to draw conclusions about the underlying cognitive processes.

Indeed, indirect methods are by far the most widely applied ones in psychology and cognitive science. One of the most common experimental methods in cognitive psychology consists of recording a person's reaction time or error rate. However, information gained by these standard indirect methods is rather sparse. Furthermore, with reaction times, it can sometimes be difficult to know exactly what can be concluded from one stimulus eliciting a response that is a mere 50 milliseconds faster than another stimulus' response. It therefore seems to be sensible to consider observing a more promising human "interface": The *eyes*.

It has been said that you can sometimes tell what a person is thinking "by the look in his/her eye", i.e. what the eye gaze is directed at. Before this *eye–mind hypothesis* (Just & Carpenter, 1987) will be considered in detail in Section 1.3, we will establish how visual information is processed in humans.

1.2 Visual Information Processing

The visual process starts when light – the visible part of the electromagnetic spectrum with wavelength ranging between approximately 400 nm and 700 nm (see Figure 1.3) – from an object in the outside world falls into the eye. The light subsequently passes through the *cornea*, the *pupil* and the *lens*. The cornea and the lens focus the light and produce a sharp upside-down projection on a light-sensitive surface that lines the rear of the eye, the *retina*, a layer of millions of *photoreceptors* and nerve cells (see Figure 1.4). The photoreceptors absorb the light and transform it into a pattern of neural activity

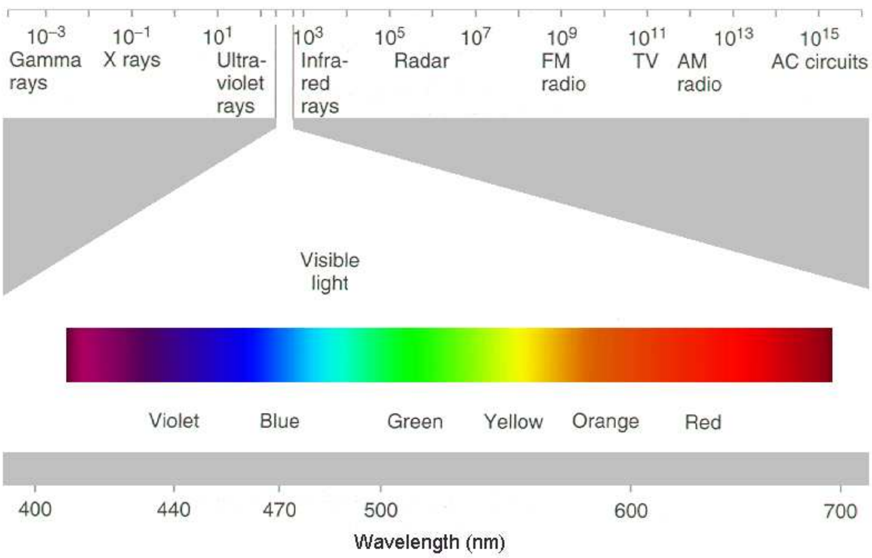


Figure 1.3: The electromagnetic radiation spectrum and the visible light spectrum, the only part that humans can see.

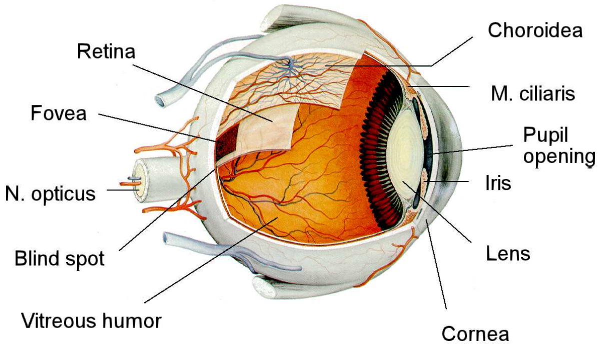


Figure 1.4: Sectional view of the eyeball (after Rohen & Yokochi, 1994).

that can be transmitted by the nerve cells, the *neurons*.

A magnified view of the retina shows the retina's complex network structure which is made up of various types of cells (see Figure 1.5, left). Photoreceptors called *rods* and *cones* act as transducers, transforming electromagnetic into "neural" energy. This data is then pre-processed by *bipolar*, *horizontal* and *amacrine cells*, which substantially compress the data, before *ganglion cells* transmit it through the *optic nerve* towards the brain for cortical processing. The retinal pre-processing is indispensable because it would be too difficult to connect all receptors directly to the relevant brain areas. Furthermore, the compression has to be performed since the capacity of the human brain is limited. Further details of the retinal structure will be discussed later in this section.

Most retinal information reaches the *lateral geniculate nucleus* (LGN), a part of the thalamus, and is passed on to the *visual cortex*, a part of the cerebral cortex, which is

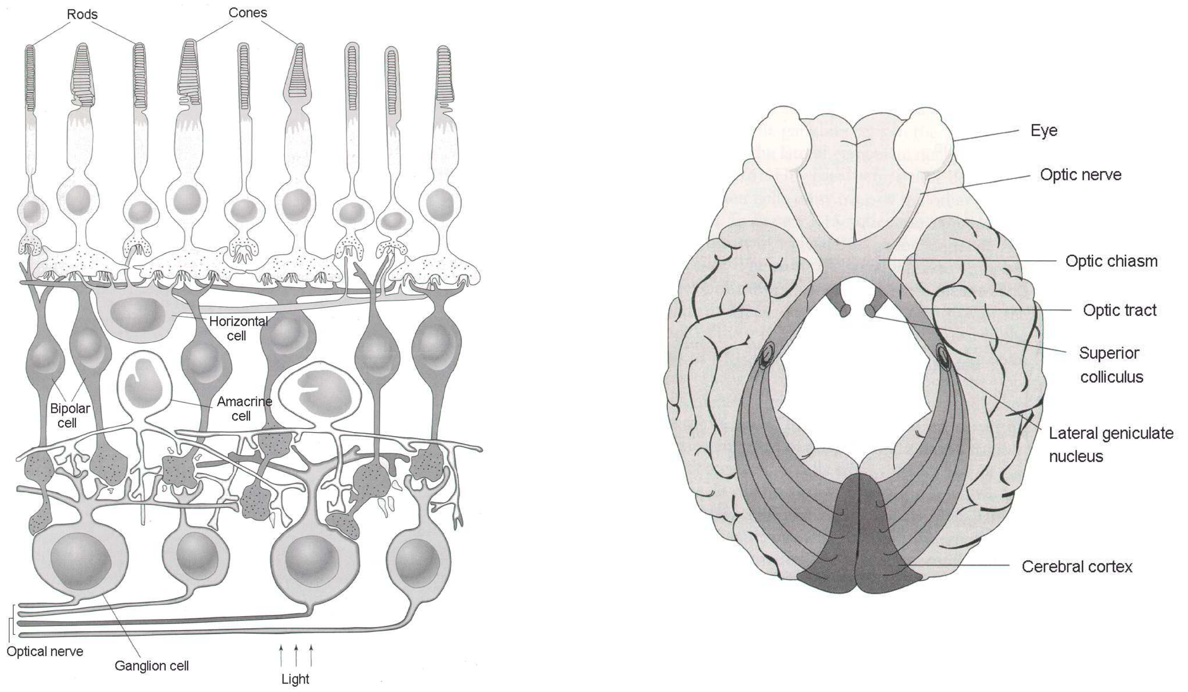


Figure 1.5: Left: Diagram of the cells in the retina. Right: The visual pathway from the eye to the brain (Matlin & Foley, 1997).

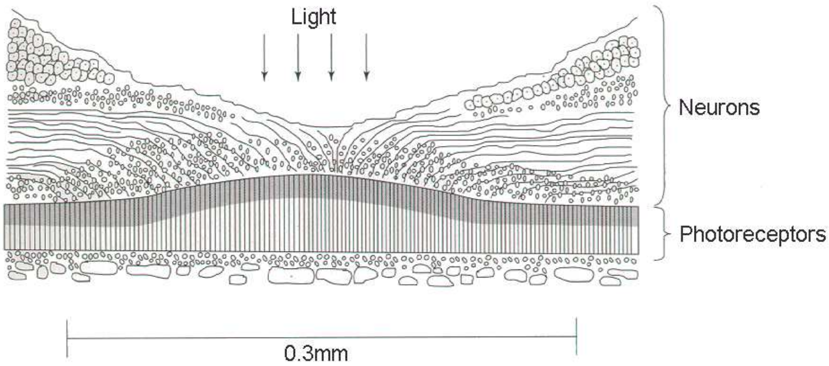


Figure 1.6: Cross section of the fovea.

responsible for higher levels of visual processing. The visual cortex is divided into the primary visual cortex (also called Area 17, striate cortex or V1) and the secondary visual cortex (also called extrastriate cortex). Cortical cells in these areas respond, for example, to lines, edges, orientation (*simple cells*), motion or colour (*complex cells*) and transmit their output to the relevant parts of the brain for further processing. Figure 1.5 (right) illustrates the visual pathway from the eye to the brain.

Let us now resume the analysis of the retinal structure. In contrast to other types of eyes, for example the compound eye of many insects, the human eye does not yield a homogeneous spatial (high) resolution over the whole field of view. Humans rather possess a very detailed vision in the center of the visual field and only coarse perception in the peripheral regions. This is due to the fact that the photoreceptors in the retina are not homogeneously distributed. The receptors are most densely packed in a small region, the so-called *fovea*, at the center of the retina (see Figure 1.6). Outside this region with a radius of about 1.5 degrees of visual angle, the density decreases exponentially with growing eccentricity. Therefore, the fovea region produces the clearest vision. For comparison, Figure 1.7 shows an image of the compound eye of a fly. The compounds are equally distributed on the eye's surface, each compound made up of arrays of light receptors. Their input can be computed in parallel and a direct link to the motor system allows the fly to rapidly respond to visual stimulus.

Humans have a single fovea located in the center of each retina; however, this arrangement is not necessarily common in vertebrates. Many mammals lack foveas and some

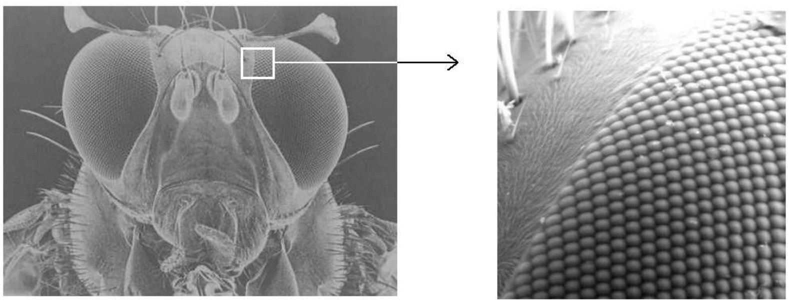


Figure 1.7: Compound eye of the fruit fly (Drosophila melanogaster).

animals, for example horses and birds, have two foveas in each eye. In horses, this is a clever evolutionary adaptation, allowing the horse to see directly ahead while seeing the ground at its feet at the same time. Still, with high spatial resolution in a very small region of the visual field only, a mechanism to shift the fovea area would be desirable to provide high resolution and a wide field of view at the same time. This is conveniently realised through *eye movements*.

1.2.1 Eye movements

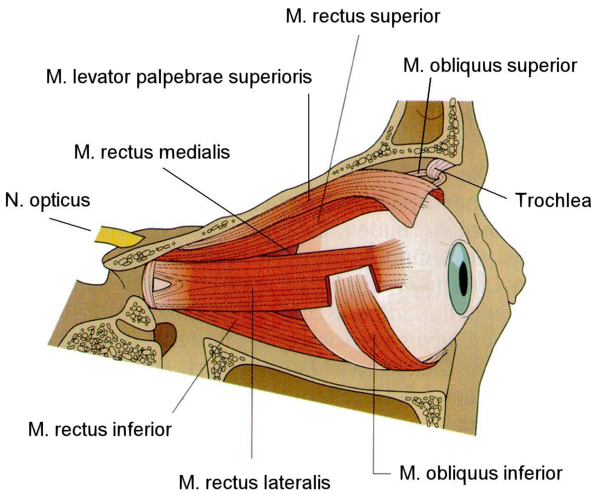


Figure 1.8: The ocular eye muscles (after Faller, 1995).

In humans, three antagonistic pairs of muscles (see Figure 1.8) move the eyeball extremely fast, reaching speeds of up to 600 degrees per second (Hallett, 1986) and allowing the eyes to move from one region of the field of view to another. This enables humans to systematically aim their eyes precisely at those regions that contain objects most relevant for the potential action that is demanding the most consideration at that point in time. The result is that people tend to look at several different objects in quick succession, and certainly not at random.

Eye movements can be classified in two basic groups, according to whether the angle between the "lines of sight" for the two eyes remains constant or changes as the eyes move: *Version* (or *conjugate*) *movements* and *vergence movements*.

Version movements describe eye movements in which this angle remains relatively constant and both eyes move in the same direction. Version movements usually occur when tracking objects that move in a plane at a fixed distance from the observer. Let us consider two important types of version movements: *Saccadic* and *pursuit movements*.

Saccadic movements

When looking at static scenes, the eyes are moved in a series of "jumps" (Huey, 1908/1968; Findlay, 1992; Irwin, 1992; Rayner, 1992) rather than continuously. The term saccadic movement refers to these rapid movements from one inspected location to the next.

During a jump, the so-called *saccade*, no visual information other than a blur (Irwin, 1993) can be perceived. The perception of visual information can only take place during *fixations*, the motionless phases between saccades. The planning of a saccade requires about 200 ms (Abrams, 1992), the time to exert the saccade itself ranges from 20 to 100 ms, depending on the distance the eyes move (Findlay, 1992). Saccade planning usually involves peripheral processing in order to determine the saccade's landing point, in particular in abstract scenarios when only little contextual information is provided (e.g. Abrams, 1992). Fixations usually last about 200 ms. However, even during steady fixations small eye movements, *micro-saccades, drifts* and *tremors* occur (e.g. Bridgeman et al., 1994). Based on the information from several fixations, the brain constructs a clear composite view of a larger portion of the visual field.

Pursuit movements

The second type of version movements are pursuit movements. They are required to track moving objects against a stationary background in order to keep objects in the fovea for greatest acuity. The two most important attributes of pursuit movements are their low velocity, typically between 30 and 100 degrees per second (Hallett, 1986), and the fact that they are smooth, in contrast to the jerky saccades. Even though smooth pursuit movements attempt to match a target's speed, they have a general tendency to "underpursue". This results in the target's image moving on the retina which makes it difficult to see details on moving images (Murphy, 1978). Figure 1.9 shows typical eye-movement behaviour in a pursuit condition when the eye follows a spot of light which acts as a target. The target starts to move at time zero. At first, the eye does not move (onset latency). Then, it starts a slow smooth pursuit movement but soon the observer realises that the target is moving ahead of the gaze, so a corrective saccade (Kapoula & Robinson, 1986) is made. After that, a smooth pursuit movement is made which follows the spot of light. This entire process only covers an angular distance of about three degrees and takes about one second.

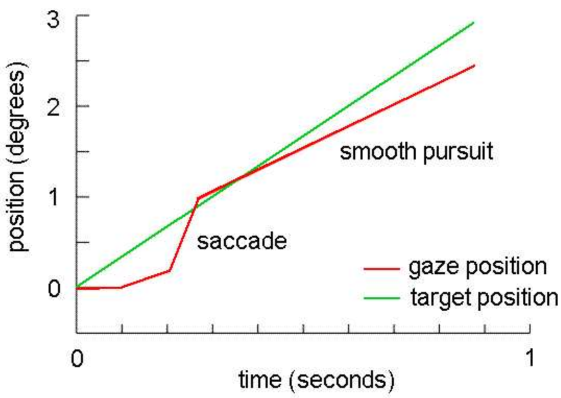


Figure 1.9: The graph shows the gaze position as a function of the position of a spot of light which acts as a target the eye is following.

Vergence movements

In contrast to the version movements discussed so far, *vergence movements* is the term used for eye movements in which the angle between the lines of sight changes and the eyes move toward or away from each other. More specifically, the eyes *converge* when looking at nearby objects and *diverge* when looking at distant ones. The purpose of vergence movements is to allow both eyes to focus on the same target in space, crucial for maintaining acuity, the precision with which we can see fine details. Compared to saccadic movements, vergence movements are rather slow; their velocities rarely exceed ten degrees per second (Hallett, 1986) and they last about one second.

Provided with the required terminology used in eye-movement research, all preliminaries should have been established for the apprehension of the *eye-mind hypothesis* that was quoted earlier. In principle, it attempts to motivate why the eyes (and eye movements) can be considered convenient indicators for mental processes.

1.3 The Eye–Mind Hypothesis

It was not until 1879 that Professor Emile Javal from the University of Paris observed that a reader's eyes do not sweep smoothly across print but make a series of short pauses at different places until reaching the end of a line. They then move to the beginning of the next in a smooth, unbroken fashion (Huey, 1908/1968). Although perhaps obvious now, these observations set in motion eye-movement research. Before Javal, it was assumed that the eyes glided unceasingly across text or other visual stimuli, a movement that offered no real insight into the underlying cognitive processes. With the new acknowledgment of non-continuous eye movements, numerous questions arose to become obvious points of departure for exploration: *Where does the eye stop? For how long? Why does it stop there? Why does it regress at times?*

According to the "eye-mind hypothesis" (Just & Carpenter, 1987), the eye commonly fixates on the symbols currently being processed by the brain. Several experiments have demonstrated that the eye can in fact be a *window to the mind*. In a typical experiment, human subjects were shown a small array of simple drawings of common objects. When the subjects were asked, "What makes of car can you name?", they tended to look at the drawing of a car while responding. Furthermore, if the subjects were asked the same question after the display was removed, they still fixated on the same position in space where the drawing of the car had been located. These results, for example, suggest that eye fixations play an important organisational or place-keeping role in cognition. More generally, the *number of fixations* and the *distribution of fixations* are thought to indicate to which extent specific stimulus regions affect perceptual and cognitive processing.

In addition, *fixation duration* can be considered as a measure of the effort of information processing. The longer a fixation lasts, the longer the visual information processing presumably takes. Prolonged fixation can, for example, be observed when *visual attention* rests on very complex regions of an image or is directed at areas that are considered relevant and of particular value for solving a given task. This relationship is strongly supported by results from reading research. The fixation duration when reading written text depends on the length of the currently fixated word and its frequency in a language (e.g. d'Ydewalle & van Rensbergen, 1993; Rayner & Sereno, 1994; Rayner, 1997). However, fixation duration does not seem to be affected by the previous word, thus the syntactic and semantic analysis of a word is evidently performed during its fixation. *Saccade length* is another basic eye-movement variable and an indicator for how thoroughly a certain region of a stimulus is scanned. Long saccades imply that a scene is only coarsely viewed whereas short saccades indicate a close inspection of stimulus details.

In summary, all types of eye movements yield data on locations and the temporal order of the acquisition of visual information which then reveals the *distribution and dynamics of visual attention*. Nevertheless, there are some restrictions concerning the link between eye movements and visual attention which might not render eye movements a perfect reflection of cognitive processes in some aspects. First, it is for example possible to fixate on a certain point in space while in fact thinking about something completely different from the scene. Obviously, eye movements do not tell much about visual attention in this case. If subjects have to solve a particular visual task, however, they should direct their attention towards the stimuli such that gaze position and attention are correlated. Second, humans are able to focus attention on different points during a fixation, i.e. shifts of attention can occur independently of eye movements. These small shifts of attention to locations within the fovea region are referred to as "covert" shifts of attention and only occur when time for extensive inspection is not sufficient (e.g. Cohen & Ivry, 1989, 1991; Treisman, 1982; Treisman & Gormican, 1988; Wolfe, 1994; Wolfe et al, 1989).

Despite these slight restrictions – which can be eliminated by careful experimental design – eye movements present a very good index of the moment-to-moment online processing activities that accompany *visual cognition tasks* such as reading, scene perception or visual search. Eye movements can give considerably greater insight into *mental processes* than simple manual response tests and allow for a more direct and convenient monitoring of these processes than image-based brain-scanning methods. As a result, eye movements have been studied in various fields of research, for example (Pomplun, 1998):

Reading research: While reading written text, a subject's eye movements tell us the duration needed for processing a particular word. These data enable scientists to draw conclusions about the structure of language information stored in our brain.

Medical research: Eye-movement measurement can help physicians to diagnose certain diseases of the nervous system, for example schizophrenia or Parkinson's disease, because these diseases lead to characteristic distortions of eye-movement parameters. Moreover, eye-movement analysis can provide information on the state of a patient's healing process during his/her therapy.

Traffic research: A car driver's eye movements tell scientists which factors distract the driver's attention and are thus likely to cause traffic accidents. The arrangement of instruments, for example, can be optimised with the help of these investigations.

Consumer research: It is important for advertising agencies to test the visual appeal of their commercial spots or brochures before launching a publicity campaign. Subjects' eye movements can indicate which parts of the spot or brochure attract most of the subjects' attention. In particular, it can be investigated whether the name of the advertised product is shown in a position in which it can be properly recognised.

After this discussion of the fundamentals of visual information processing, types of eye movements and a motivation and validation of their function as indicators for cognitive processing, the following section addresses the methodological aspects of eye-movement research: *How can we measure eye movements?*

1.4 Tracking Eye Movements

Let us recall some of the obvious questions often asked in eye-movement research: Where does the eye stop? For how long? Why does it stop there? It becomes clear that the plain measurement of the eyes' sensorimotor data (*oculomotor* data), i.e. the movement of the eyeball, is not sufficient for most research purposes. Instead, the *gaze position* within the presented visual stimulus, usually a two- or three-dimensional image, is required for analysis. Consequently, body or head movements have to be measured (or eliminated) and their orientations have to be considered as well for the computation of the gaze position. Taking these requirements and research goals into account, *gaze trajectories*, i.e. spatio-temporal scan paths constitute the optimal data to be obtained from *eye-tracking* experiments.

Thus, various techniques to accurately track eye movements were developed alongside the ongoing research. Since the early experiments (see Figure 1.10) conducted at the beginning of the twentieth century, for example Dodge (1900), Buswell (1922, 1935, 1937) or Judd and Buswell (1922), eye-tracking techniques have steadily improved. They now allow for extremely accurate and high-resolution eye tracking. Young and Sheena (1975) and Lee and Zeigh (1991) is recommended reading for a comprehensive survey of methods for measuring eye orientation. The following paragraphs provide an overview of selected eye-tracking methods.

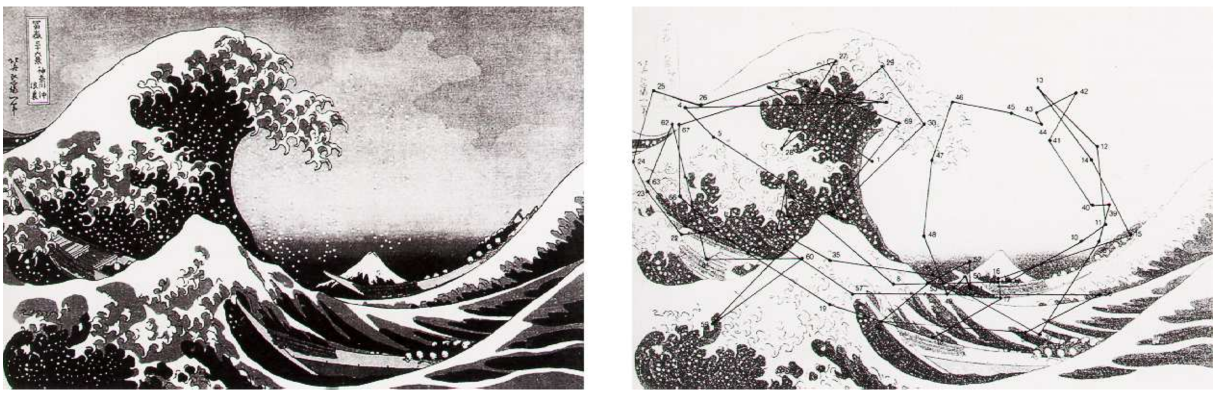


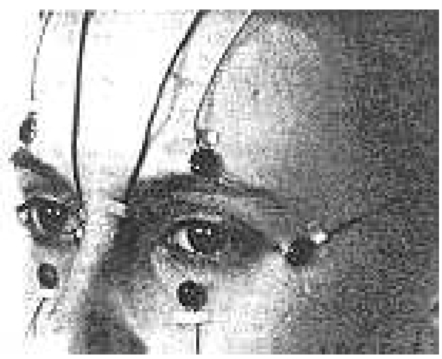
Figure 1.10: Early record of eye movements (Buswell, 1935) during free examination of the painting "The great wave of Katsushika Hokusai" (1760–1850).

Electrooculogram (EOG)

Mowrer, Ruch and Miller (1936) discovered that eye movements can be measured by means of attaching electrodes to the facial skin around the eyes (see Figure 1.11, left). The electrodes measure the potential variation between the cornea and the retina. The voltages of this so-called *corneo-retinal potential* vary when eye movements are exerted and typically range from 0.4 to 1 mV. The EOG method can detect eye movements up to $\pm$ 70^o (approximately 70% of the visual field in binocular vision), the spatial accuracy reaches 1.5 to 2^o of visual angle. However, accuracy for vertical movements in particular deteriorates rapidly in peripheral regions. Furthermore, EOGs are prone to error or artifacts caused by the activity of muscles surrounding the eyes, blinking movements or changing light conditions during an experiment.

Contact lenses

Either (a) minute mirrors that reflect a narrow IR-light ray onto a photosensitive material (see Figure 1.11, right) or (b) minute induction coils ("eye coils") are attached to a rigid contact lens that moves analogously with the eyeball. Here, the subject's head is surrounded by a box wherein an electromagnetic field is generated that induces a low current into the eye coils. Eye movements result in variations of the induced currents which then yield highly accurate data on the eye position (5 to 10 seconds of arc), but in a very narrow field of view of only 5^o. A major disadvantage of both (a) and (b) are the severe restrictions that have to be imposed on the subjects' freedom of action and the fact that an artificial object has to be placed on the cornea. Method (a) in particular requires a rather unpleasant fixation of the head, often achieved by individually adapted bite bars to minimise head movements during an experiment. Furthermore, early experiments using the (mirror) contact lens method (Yarbus, 1967) did not yield any temporal information on eye movements and the recorded scan paths only indicated the regions of the presented stimulus upon which the eye focused most. Today, the (coil) contact lens method is mainly used in micro-saccade research and for investigating torsional eye movements.



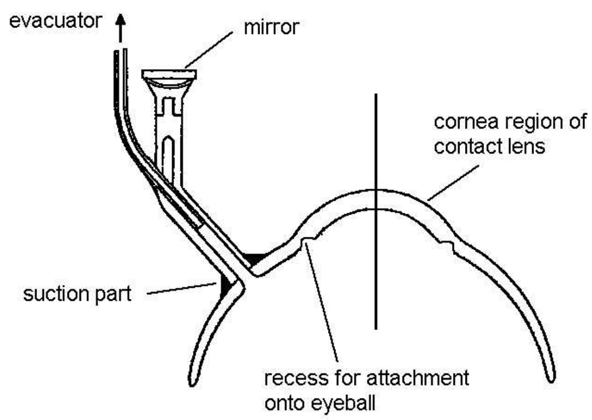


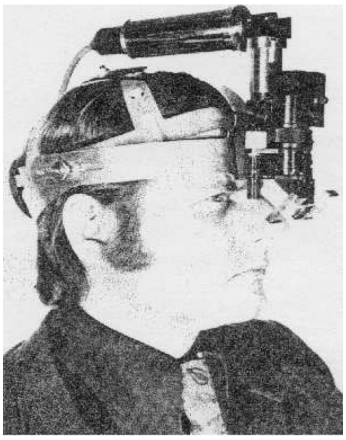
Figure 1.11: Left: Arrangement of electrodes for an EOG. Right: Schematic view of a mirror contact lens.

Corneal reflection

In the late 1960's Kenneth Mason developed the theory for the corneal-reflection method. It describes an automated procedure for observing the eye using a camera, measuring the locations of the pupil center and corneal reflection, and calculating the direction of gaze (Mason, 1969). In the early 1970's John Merchant and Richard Morrisette built a system that implemented the concept in practice (Merchant & Morrisette, 1973). Their "oculometer" employed a video camera to observe the subject's eye and a computer to process the camera's image of the eye (see Figure 1.12, left). Their image processing algorithms consisted of innovative methods to (a) recognise the pupil of the eye and calculate its geometrical center, and (b) locate the relative position of the corneal reflection. They introduced the use of higher order polynomial equations to correct for non-linearities in the oculometer, and they developed root-mean-square regression methods for calibrating the equations to individual people's eyes.

Purkinje Images

Cornsweet (1973) developed the Purkinje image method. This method uses a camera and an IR-light source and computes the eye's orientation based on light reflections from both the front and rear surfaces of the lens of the eye. Because it does not depend on the pupil opening and closing concentrically about the eye's optic axis, the Purkinje image method can be more accurate than the corneal-reflection method. However, it requires a significantly more controlled lighting environment to be able to detect the rear surface reflection of the lens of the eye. Figure 1.12 (right) illustrates how the reflections of the light beam create the Purkinje images.



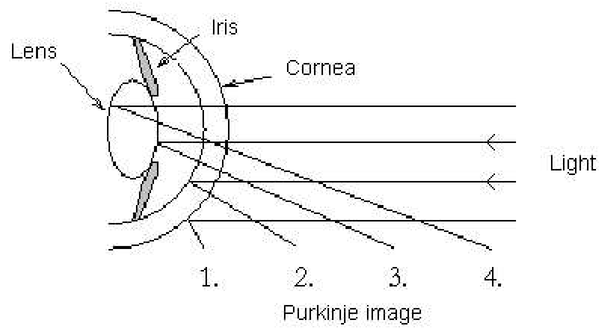


Figure 1.12: Left: Apparatus used for tracking eye movements with the corneal reflection method. Right: Reflections from cornea and lens yield Purkinje images.

Pupillography

Applying video-based techniques and an image-processing system, either the border between the iris and the sclera (limbus tracking) or between the pupil and the iris (pupil

Figure 1.13: Left: Limbus tracking. Right: Pupil tracking.

tracking) are detected and tracked (see Figure 1.13). Measurements within $\pm 15^o$ can be achieved with an accuracy of 0.1^o. The tracking of vertical eye movements presents problems using these methods because the eyelid can cover relevant parts of the tracked target.

Evidently, the technologies discussed impose severe limitations on the design and conduct of eye-tracking experiments in many aspects. Most methods rely on fixing the subject's head during the experiment. Using a bite bar or chin and head rests neither provides comfortable conditions, nor can the experimental environment be considered "natural" with technical apparatuses surrounding the subjects. This often causes artifacts in the recorded data which might then lead to wrong conclusions about perception processes. Furthermore, such methods cannot be used in scenarios that require, for example, language production or interaction with the environment. In addition, lengthy setup and calibration procedures are often necessary before the start of an experiment. Attaching objects, such as contact lenses, to the cornea presents a potential health hazard. Finally, the lack of a temporal log of eye movements makes a comprehensive data analysis impossible.

However, with the development of digital cameras, powerful image processing devices and the recent advances in miniaturisation, many of these restrictions can be overcome. Today, a state-of-the-art eye-tracking system employs miniature, headband-mounted video cameras to monitor eye movements. The video data is transferred to a computer that executes the image processing online and digitally stores the relevant eye data, for example gaze position or pupil size, along with a time stamp. This data is then available for quantitative post-processing or can even be fed back into the system for gaze-contingent, online manipulation of the stimulus display. The image processing system usually works on variants of the corneal-reflex or pupil-/limbus-tracking methods. Fixation of the subject's head is no longer necessary either. Many modern eye-tracking systems allow for head-movement compensation – i.e. the head's position relative to the stimulus display is taken into account when computing the gaze position – so that subjects can move around naturally and even walk short distances.

The Neuroinformatics Group at the University of Bielefeld currently avails of two of these advanced eye trackers, namely the SR Research *OMNITRACK1* and its successor, the SMI *EyeLink*. All experiments reported in this dissertation were conducted with the SMI EyeLink. The following paragraph provides only a brief overview of the EyeLink eye tracker. Details will be discussed in the context of the methodological preliminaries of the experiments in Section 3.1. Stampe (1993) is recommended reading for obtaining further information on the underlying technical principles of both OMNITRACK1 and EyeLink systems.

The SMI EyeLink Eye Tracker

The main component of the SMI EyeLink eye tracker is a lightweight headband on which three digital cameras are attached: Two *eye cameras* (one per eye) recording images of the eyes as they move, and a *head camera* recording an infra-red (IR) image of the subject's field of view (Figure 1.14). The two eye cameras facilitate *binocular* eye tracking. Convergence movements and gaze positions in three dimensions can easily be determined from their separate recordings. The key information contained in the head camera's image is the position of four IR light emitting diodes (LEDs) that have to be attached to the corners of the stimulus display, usually a computer screen. The subject's head position relative to the screen can be computed from the location of the IR LEDs which appear as bright spots in an otherwise dark head-camera image. The eye cameras are linked to an image processing interface that derives the pupil positions from the cameras' images. Using a non-linear projection, the aggregated head and pupil positions are then mapped onto the display coordinate system, yielding the desired gaze position. In order to determine the projection's parameters, a *calibration procedure* has to be performed prior to an experiment. Here, a target marker sequentially moves across the screen while subjects visually track it. The calibration procedure can be completed within 30 seconds and leads to a high spatial accuracy of eye gaze measurement in the subsequent experimental recording. In summary, the SMI EyeLink eye tracker provides both natural conditions

Figure 1.14: Headset of the SMI EyeLink eye tracker.

for subjects (freedom of head movements) and a highly accurate measurement of binocular eye-movement data. Furthermore, as the gaze position data is available online, the SMI EyeLink eye tracker can be used for gaze-contingent experiments.

Both the technical equipment and the apparent validity of eye movements as indicators of perceptive and cognitive processing in the human brain – as described above – now leave us with the challenge of selecting a promising research paradigm to explore. This choice should mainly be guided by the consideration whether, compared to more "conservative" methods, the measurement of eye movements and the investigation of eye-movement parameters yields new insight into visual processing given a certain task or not. Relevant aspects to be considered in this respect are:

- Which stimuli are presented?
- What is the subjects' task?
- Which hypotheses are to be tested?
- Which are the relevant eye-movement parameters to be investigated?

Chapter 2

Visual Comparison and Assessment of Object Proportions

2.1 Visual Comparison

Research in the Neuroinformatics Group at the University of Bielefeld has rendered the eye-tracking methodology particularly useful for investigating the paradigm of *visual comparison* (e.g. Koesling, 1997; Pomplun, 1998; Pomplun & Ritter, 1999).

In principle, all studies concerned with the paradigm of visual comparison use a similar experimental scenario: Two stimulus pictures A and B are shown either simultaneously side by side or sequentially one after the other. Subjects then have to decide, for example, whether A and B are identical or different. If A and B are found to be different, subjects may also have to state the type of difference. Alternatively, for more complex tasks, subjects are asked to match A and B: They have to manipulate A so that it looks like B.

Furthermore, it can be assumed that all visual comparison tasks share a common *cognitive structure*. In order to solve such a task, apparently the following processing steps have to be accomplished:

(a) Assessment of A.

(b) Memorisation of A.

(c) Assessment of B.

(d) Comparison/matching with A.

A closer inspection reveals that each step describes quite complex *perceptual* and *cognitive* processes. It is, for example, not intuitively clear how humans assess a specific stimulus picture. Which factors determine visual scan path, how do these contribute to the memorisation of relevant attributes of the picture? Which information is included in the memorised "percepts", how are these mentally represented? Is any of the memorised information lost until the representation is recalled for comparison? What exactly is compared, how is the comparison/matching process accomplished?

Apparently, the answers to these questions are closely related to the *experimental design*. The essential aspects with respect to the experimental scenario and the specific task will thus be discussed in the following.

First, the *choice of stimuli* certainly has a great impact on visual comparison tasks and the cognitive processing steps. The investigation of different *types of stimuli* thus appears to be a promising strategy for the systematic exploration of the paradigm of visual comparison. Stimuli can, for example, be varied along three characteristic "axes" of stimulus properties:

- Semantic content.
- Stimulus dimension.
- Stimulus distribution.

Along the axis of *semantic content*, investigations may focus on *abstract* stimuli or on *realistic* scenes. Abstract stimuli do not carry much *conceptual* information and their visual processing only involves factors operating on a low semantic level – such as colour, shape or spatial arrangement. In contrast, the visual processing of realistic scenes involves factors operating on a high semantic level. Humans usually have a specific *concept* of how to perceive such scenes. This knowledge is likely to influence eye-movement patterns. Experiments using ambiguous pictures (Pomplun, Ritter & Velichkovsky, 1996), for example, have shown that the distribution of attention is not only influenced by the geometrical properties of the stimulus, but also by the semantic interpretation of the picture elements. Although conceptual factors are difficult to parameterise and hence difficult to access for quantitative analysis, realistic scenes are preferable to abstract ones: They provide a higher *ecological validity*.

The choice of the *stimulus dimension* can also be considered in terms of ecological validity. In everyday life, humans usually perceive and manipulate three-dimensional objects in three-dimensional environments. Using lower-dimensional stimuli in experiments would thus not exactly present ecologically plausible situations. On the other hand, the perception of *realistic*, three-dimensional scenes involves processes on a higher semantic level. This would render data analysis and interpretation more complicated (see above). *Abstract* three-dimensional objects could be used in an attempt to exclude semantic factors such as knowledge or interpretation. However, in comparison with one- or two-dimensional stimuli, the visual perception of three-dimensional still requires processing on a higher semantic level due to the influence of object depth.

Alternatively, two-dimensional stimuli that can be interpreted as three-dimensional objects can be used instead of real three-dimensional objects. Most of these stimuli, however, are not ideal for eye-movement investigations. In particular stimuli consisting of abstract objects do often not yield stable three-dimensional visual representations. Experiments using the so-called "Necker-Cube", for example, have shown that the distributions of attention significantly differ for the two possible spatial interpretations (Pomplun, Ritter & Velichkovsky, 1996). This interpretation "flipping" does not facilitate the interpretation of eye-movement pattern – unless the the investigation focusses on the “flipping” iteself. Consequently, abstract geometrical one- or two-dimensional stimuli should be preferred in order to minimise the influence of higher semantic processes on visual perception. “Simple” objects, for example one-dimensional line segments or basic two-dimensional figures such as circles or squares, can reliably be defined using few dimension parameters such as length, size and orientation.

The *stimulus distribution* describes the *number of stimulus constituents* and their *spatial arrangement*. Variation along this axis of stimulus properties must be considered in the context of the *type of the visual comparison task*. Using only few constituents to form a stimulus picture, the visual assessment can be assumed to focus – or, more appropriately: to foveate – on the constituents and their details. Such sparse, localised distributions should thus be convenient for the assessment of *individual object properties* or *proportions*, i.e. for the investment of *local, detailed* visual perception processes. In fact, *single objects* rather than object distributions would constitute appropriate stimuli for such investigation purposes.

In contrast, distributions of *numerous* stimulus constituents that are *widely spread* across the stimulus picture can conveniently be used to study more *global* aspects of visual comparison. Here, the global characteristics of a visual scan path should be in the focus of the investigation. It can be assumed that such scan paths are also influenced by the local properties of the stimulus constituents. These, however, are not likely to be visually examined in details.

The strategy to systematically explore different types of stimuli and different types of visual comparison tasks has been successfully pursued in recent studies at the University of Bielefeld. The visual comparison tasks of *comparative visual search* and *numerosity estimation* were explored. According to the eye-mind hypothesis, eye movements were investigated in order to gain the desired insight into the underlying cognitive processes.

Comparative visual search tasks investigated abstract and realistic scenarios, using low- and high-dimensional stimuli. Stimulus pictures usually contained large numbers of constituents in both comparative visual search and numerosity estimation tasks. As a consequence, the investigations primarily yielded information about *global* processing mechanisms during the assessment and comparison of widely *distributed* stimuli. Only little insight could be gained into *local* visual comparison processes. The following paragraphs briefly summarise the recent investigations and present their key results.

Abstract Comparative Visual Search

In comparative visual search subjects had to detect a single mismatch (in either colour or form) between two otherwise identical, simultaneously presented images. These images consisted of large numbers of abstract items (see Figure 2.1, left). Various studies have shown, for example, that the task completion involves two distinct phases (Pomplun, 1998): First, subjects serially search the images for the mismatch. This results in pendulum-like eye movements, comparing one or more memorised items, depending on parameters like object density or entropy, in corresponding areas of both hemifields. Sec-

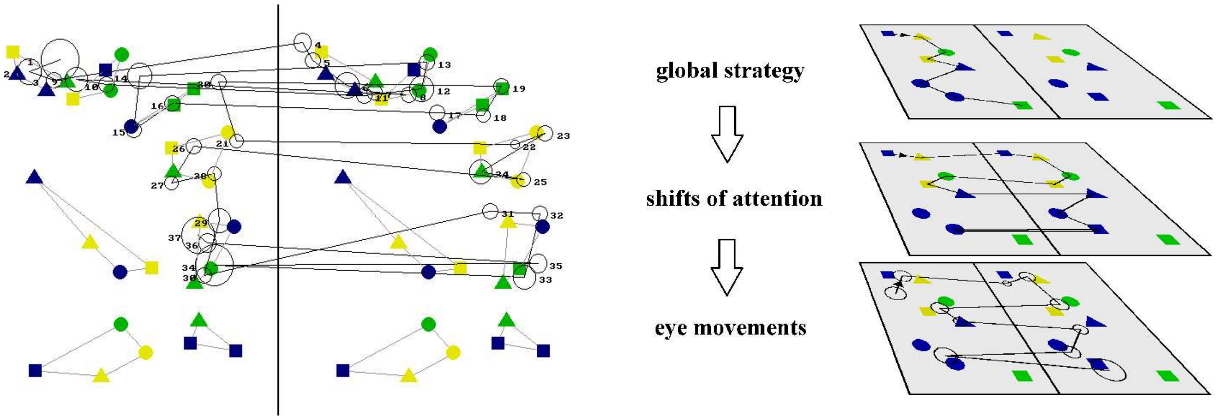


Figure 2.1: Left: An abstract sample stimulus as presented in comparative visual search studies. Left: A three-level model for comparative visual search (in Pomplun, 1998).

ond, when the mismatch is found, the eye gaze shifts back and forth several times between the targets to verify the mismatch. Eye-movement parameters varied significantly between colour and form search, when “top down” information (subjects were informed about the relevant mismatch dimension prior to the experiment) or “bottom up” information (the irrelevant mismatch dimension remained constant) was provided: Search scan paths and therefore reaction times were generally shorter for colour search and in the “top down” and “bottom up” conditions.

These and further findings were formalised in a “three-level model” (see Figure 2.1, right). This model adequately simulate the human visual scan path for the given comparative search task that used distributed, abstract stimuli. Further information can be found in Pomplun and Ritter (1999) and Pomplun et al. (2001).

Conceptual Comparative Visual Search

The abstract stimuli used in the previous experiments allowed to draw conclusions mainly about perceptual and “low-level” cognitive processing strategies in visual comparison tasks. The stimuli used were not suitable for investigating the influence of cognitively more complex, conceptual information on such tasks. Moving along the “axis” of semantic content, stimuli that now could be semantically interpreted were used in a comparative visual search scenario. In order to investigate the transition between perceptual and “high-level” cognitive processing levels, so-called “Mooney Faces” were chosen as stimuli. This type of stimulus was rendered ideal for the investigation: When presented in an upright orientation, the black and white regions can be interpreted as *faces*. A rotation of 180^o transforms the stimuli into images with *no semantic content*, they only seem to show random arrangements of black and white regions.

The investigation yielded rather unexpected results. Basically, no significant differences were found in the eye-movement data between the upright and rotated conditions. These findings suggest that similar visual comparison strategies are used, irrespective of the semantic content of the stimuli. Alternatively, it can be speculated that the comparison strategy differs between the two levels of semantic content, but that this does not

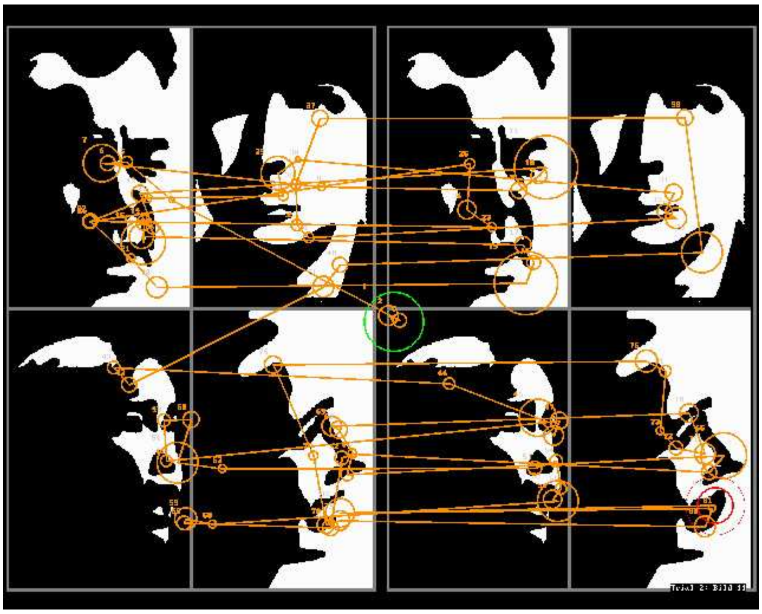


Figure 2.2: A sample stimulus as presented in comparative visual search studies, overlaid with a gaze trajectory.

show in the measured variables. It appears more likely, however, that the chosen stimuli were not entirely suitable to investigate the transition between the different semantic levels. The recognition of faces in the stimuli might have been too "costly" and subjects applied the same visual scanning strategy in both the upright "faces" and the rotated "random" scenarios. This strategy is guided by geometrical factors rather than by conceptual considerations. Figure 2.2 shows a typical gaze trajectory for an upright "faces" stimulus.

Numerosity Estimation

With the previous study demonstrating that conceptual, semantic content is quite different to parameterise, the row of visual comparison investigations returned to abstract stimuli. Now another task was explored: Numerosity estimation. As for abstract comparative visual search, stimulus pictures consisted of large numbers of items. As a consequence, the findings of the investigations must primarily be viewed with respect to *global* processing mechanisms.

The influence of structural information on the perception of numerosity in two-dimensional object distributions was determined in several studies (see Figure 2.3). When subjects tried to adjust the number of items in the stimulus' right hemifield so as to match the number on the left, this generally resulted in an underestimation. Furthermore, the intensity of underestimation varied, for example, with the overall item number, cluster size and different types of structural information.

Again, eye-movement recordings yielded valuable information to help explain the observed behaviour: Instead of single items, clusters were fixated as a whole and attention was mainly focused on areas with high object density in proximity to the stimulus cen-

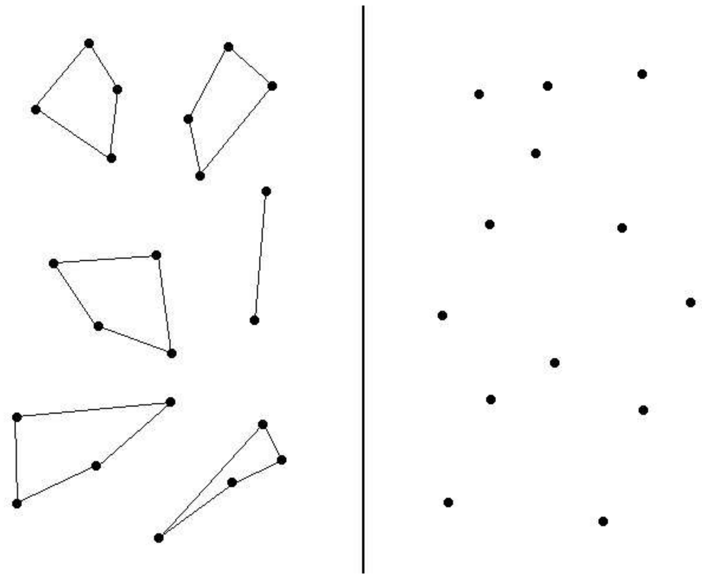


Figure 2.3: A sample stimulus as presented in numerosity estimation studies (Koesling, 1997).

ter. In contrast to fixation durations which significantly rose with increasing numbers of items, the number of fixations remained constant. It appears that the number of (central) clusters was somehow incorporated into the numerosity estimation, leading to an underestimation effect that increased when more items were presented. Prolonged fixations are obviously not suitable to compensate for the "laziness" of not executing further fixations as would be necessary to correctly perceive the surplus information. The implementation of a model based on neural information processing principles, so-called "receptive fields", scored well at simulating the underestimation effects as observed in humans. An in-depth discussion of all aspects of these studies is documented in Koesling (1997) and Koesling et al. (submitted).

The Next Step: Assessment of Individual Objects

The successful application of eye-tracking methods yielded novel insights into human visual information processing regarding the above-mentioned comparison tasks. It now appears to be quite rewarding to transfer this previous experience to a similar, but new domain. Furthermore, problems should be addressed that appeared imminent, but were yet unattended. The aim must be to complement the current image of processes guiding visual comparison in order to obtain a (more) *comprehensive* understanding of this research paradigm. In fact, the following studies can be motivated quite naturally by moving further along the different "axes" that have determined the type of stimuli and guided the investigations so far.

With a view to the axis of *stimulus distribution* it is quite clear where investigations should move to: In contrast to analysing visual processes on a rather *global* – or *macro* – level as has been done so far, particular attention should now be paid to the *local* – *micro* level. The key question must now be: How do humans perceive *individual objects*?

Let us also consider *semantic content*. Stimuli with both low and high levels of conceptual information were explored so far. The findings clearly demonstrated that experimental control is apparently compromised when stimuli with a high level of conceptual information have to be assessed. It must in general be considered quite difficult to attribute specific observations to conceptual influence or to other, more abstract, factors. The use of *abstract stimuli* that can be reliably parameterised should thus be recommended, in particular with regard to the interpretation of eye-movement parameters.

That leaves us with the choice of convenient *stimulus dimensions* and the choice of an appropriate *comparison task* to explore the perception of abstract, individual objects. Let us consider the choice of the comparison task first.

A promising paradigm in this context appears to be the *visual perception and assessment of proportions* of objects, embedded into the overall paradigm of visual comparison. The principal experimental scenario of the investigation within this thesis is thus fairly exactly specified: Two abstract, individual objects will be presented either sequentially or simultaneously. The subjects' task will then either be to decide if the stimuli are identical – or different – or they have to state the type of difference. Alternatively, for more complex tasks, subjects will be asked to match A and B with respect to the proportion in question. This also means that the cognitive structure outlined earlier is preserved: Assessment, memorisation, comparison. Accordingly, the investigations will again focus on the accomplishment of these processing steps.

But is proportion assessment indeed suitable for eye-movement research? In order to understand why objects are perceived in a specific manner the following questions must be addressed: Which factors influence perception when assessing object proportions, what effects do they cause and how can these effects be explained? Which proportions should be investigated? Which hypotheses can be advanced regarding the details of the cognitive structure for such comparison tasks?

These questions certainly cannot be answered instantly. The following sections try to clarify the essential preliminaries and give an overview of previous work in this scientific field. This allows us to more specifically determine the experimental structure and to hypothesise particular aspects of the cognitive structure that the investigations will focus on. The following sections will also render some *stimulus dimensions* more promising than others – a relevant aspect that has not been decided on yet.

2.2 Assessment of Object Proportions

Let us first consider what exactly the term "object proportions" means and how these proportions can possibly be assessed.

In general, the term refers to the various *physical dimensions* or *attributes* of an object or a physical phenomenon. Such dimensions could, for example, be the *weight* of a solid object, the *length* or *orientation* of a line segment or the *amplitude* and *frequency* of a sound.

The assessment of proportions evidently requires the *perception* of the respective object and includes all *sensorimotor*, *perceptive* and *conceptual* processes. Consequently, the "percept" is not a simple representation of physical evidence, but a combination of information from different cognitive processing levels. Stimulation from sensorimotor receptors – for example from *visual, tactile* or *auditory* channels (or a mixture of them) – is evaluated along with prior knowledge or contextual data. Thus, the finally emerging result is often a somewhat "distorted", subjective internal representation – the so-called *mental model* (Johnson-Laird, 1983) – of an object or a scene. If, for example, subjects have to lift various objects and judge their weights with regard to a standard, different object sizes can lead to changes in the perceived weights, even if their masses are identical. This makes clear that, when assessing object proportions, the perceived proportions do not necessarily coincide with the original ones.

In fact, research into the assessment of object proportions has a long history. Pertinent experiments have proven rather popular in the past – early systematic recordings dating back to the 1830s (Wheatstone, 1838) – and at present. However, as the following paragraphs will demonstrate, fundamental principles are still not understood. Various different hypotheses exist to explain particular phenomena only and often rather specific cases were/are addressed. Many studies deal(t) with the assessment of *length, size* and *orientation*, primarily concerned with phenomena of *visual illusions*, namely *geometrical illusions*.

Visual Illusions

Of all such illusions, the *Müller-Lyer illusion* is one of the most thoroughly examined: Two line segments – "shafts" – of equal physical length are presented parallel to each other. Attached to the line segments' end points are arrowheads, pointing either inward (obtuse angle) or outward (acute angle). In this classical form (Müller-Lyer, 1889), the illusion consists of the obtuse-angle illusion of shaft overestimation and the acute-angle illusion of shaft underestimation (see Figure 2.4 (a)).

The illusion has been studied extensively, partly because of the belief that the understanding of visual illusions can reveal the principles governing non-illusory visual perception (Warren, 1976; Warren & Bashford, 1977). It is well accepted that the human visual system decomposes an image using local filters tuned for stimulus features, such as spatial frequency or orientation (Campbell & Robson, 1968; Kulikowski et al., 1973; Sagi & Hochstein, 1983). Psychophysical and physiological evidence suggests that the local filters are not completely independent (Polat & Sagi, 1993; Kapadia et al., 1995; Chen & Levi, 1996). Rather, they receive input from filters coding for neighbouring spatial frequencies and orientations, thus suggesting interactions between neighbouring channels. This network of long-range inter-connections may serve as substrate for context dependence, i.e. the fact that the perceived visual attributes of a target stimulus depend on the context within which the target is placed. Consequently, the Müller-Lyer illusion with its context-induced subjective distortion of shaft length is a prime example of where these interactions are involved.

Various theories were offered to explain the classical Müller-Lyer illusion. The *depth* or *linear perspective theory* (Gregory, 1963; Gillam, 1998) relies on direct size scaling mechanisms and hypothesises that length distortions are due to misapplication or confusion of size constancy to the two spans. The perceptual assimilation of the length of the shaft towards the lengths of the wings – or the contextual elements in general – serves as a basis for the *averaging theory* (Day & Dickinson, 1976; Brigell et al., 1977; Pressey & Pressey, 1992). This theory assumes that the arrowheads interfere with the perceptual system for measuring the span of the horizontals and therefore observers confuse or average the distance between the arrowhead tips. Other approaches (Chiang, 1968; Stuart, et al., 1984; Morgan et al., 1990; Glennerster & Rogers, 1993) hypothesise the incorrect encoding of the positions of the vertices of the wings – *displaced vertex theory*, in which the perceptual system miscalculates the location of the arrowhead vertex, displacing it toward the concave side. Finally, properties of the low frequency visual channels (Ginsburg, 1984) and object recognition processes, such as mechanisms associated with preperceptual adjustments (Warren & Bashford, 1977) and visual scene interpretation (Redding & Hawley, 1993; Redding et al., 1993) are thought to be responsible for the illusion (see Figure 2.4 (b)). It has been found that vertices presented in isolation have consistent and predictable effects on size scaling and should therefore be unambiguously interpreted. This is consistent with current computational theories of object recognition, for example when modelling the interpretation of line drawings (e.g. Guzman (1968); Waltz, 1975; Biedermann, 1987; Malik, 1987; Winston, 1992).

In fact, the Müller-Lyer illusion can be observed for various variants of the original stimuli. The illusion persists even when the shafts are absent and the distance between the arrowheads has to be estimated. Replacing the arrowheads with other symbols still results in incorrectly perceived length (see Figure 2.4 (c)). Several studies were concerned with the effect of the arrow angle on the magnitude of the illusion. Erlebacher and Sekuler (1969), for example, found a less pronounced under-/overestimation of line length when the angle was increased. Using different colours for shafts and arrowheads reduced the magnitude of the illusion as well (Sadza & de Weert, 1984). Schulz (1991) demonstrated that a delay of between 35 to 400 ms between the presentation of shafts and arrowheads still caused the

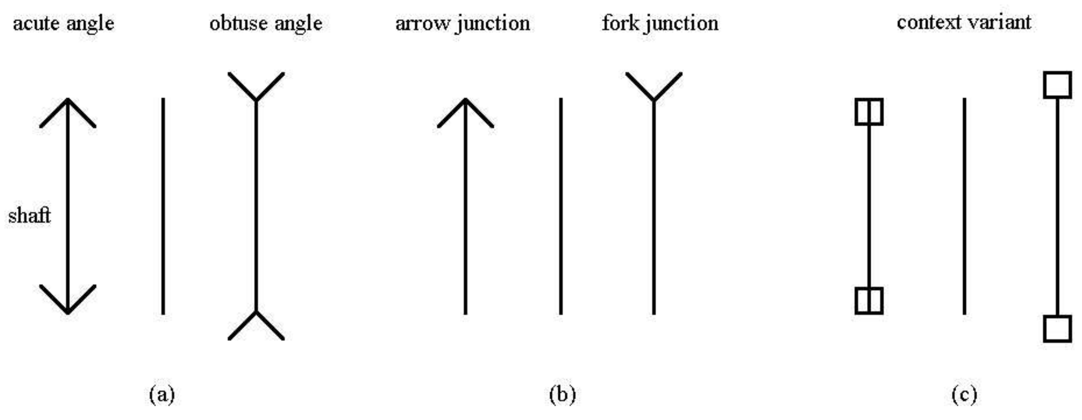


Figure 2.4: (a) Original Müller-Lyer illusion stimuli. (b) Vertex labelling as used in line-drawing interpretations by Waltz (1975) and Winston (1992). (c) Context variant where arrowheads are replaced by boxes. Notice that the illusion still persists.

illusion. Another interesting finding suggests that the magnitude of the illusion decreases with increased presentation times of the stimuli (Brosvic et al, 1997). It was shown that the illusion can even be induced by only imagining the arrowheads (Berbaum & Chung, 1981). Furthermore, McKelvie (1984) established a task-effect of the psychophysical method on the illusion magnitude. He found a less intense illusion for the so-called "method of adjustment" compared to the "method of constant stimuli" and the "method of limits"[1]. Finally, the alignment and the spatial locations, i.e. distance, of the two line segments influence the illusion. Pressey and di Lollo (1978), for example, observed a decreasing illusion the further the two line segments were positioned apart.

Whereas the added information in the one-dimensional Müller-Lyer figures caused a distorted perception of *length*, a similar effect emerges for perceived *size* in the two-dimensional Ebbinghaus illusion (also called Titchener illusion; see Figure 2.5, left). Here, small circles lead to the overestimation of the size of the central circle they surround. Vice versa, surrounding large circles lead to the underestimation of the size of the central circle. In the *Delbœuf* figure (see Figure 2.5, right), the left outer circle appears larger than the right inner circle.

Figure 2.5: Left: Original Ebbinghaus illusion stimuli. Right: Original Delbœuf illusion stimuli.

Compared with the Müller-Lyer illusion, not quite as many studies are concerned with the Ebbinghaus and Delbœuf illusions. Major works examined proximity effects of the surrounding circles in the Ebbinghaus illusion. Weintraub (1979), for example, found a decreasing magnitude of the illusion with increasing distance between central and surrouding circles. A study by Coren and Enns (1993) supported the assumption that a figural similarity between central and surrounding items (not necessarily circles) resulted in a larger magnitude of the Ebbinghaus illusion. A successive presentation of the central items and their context, in contrast, reduced the illusion or even caused it to completely disappear (Jaeger, 1978). Contrast variations revealed similar effects (Jaeger & Pollack, 1977).

In order to understand the Ebbinghaus illusion, the averaging theory (see above) – alternatively referred to as the *contrast and assimilation theory* – is frequently quoted. Within the Ebbinghaus figure, the illusion is assigned to the overestimation of the size differences ("contrast") between the circles. However, the contrast and assimilation theory

[1]The *method of adjustment* allows subjects to continuously vary a stimulus, i.e. its relevant dimension/intensity. In contrast, stimuli are controlled by the experimenter when the other methods are applied. In the *method of constant stimuli*, stimuli are presented in random order. Employing the *method of limits*, stimulus intensities are successively increased or decreased from trial to trial.

only facilitates the classification of various illusions, but it neither explains the underlying perception mechanisms nor their functions. It even cannot be applied to some illusions, for example to the Poggendorff (see Figure 2.6, left) or the horizontal-vertical illusion (see Figure 2.6, right).

The horizontal-vertical illusion was one of the first to be experimentally studied (Künnapas, 1955) and is of particular relevance with regard to the research reported in the following chapters. Individuals adjusting vertical line segments to equate to corresponding horizontal line segments are prone to perceptual errors: The vertical line segment is usually made shorter than the horizontal line segment.

Figure 2.6: Left: Original Poggendorff illusion stimuli. Right: Original horizontal-vertical illusion stimuli.

An early explanatory theory was put forward by Segall et al. (1966) and represents a perspectivist's view along the lines of Gregory's (1963, 1970) constancy-scaling theory, which presumes an apparent expansion of space in the upper part of the visual field: If a vertical line appears longer than an objectively equal horizontal line because it is interpreted as located on a plane receding or partly tilting away from the observer, then two parallel vertical lines should appear to be diverging from each other at their upper ends. In fact, Piaget's (1969) studies of the horizontal-vertical illusion seem to support this theory: If the horizontal and vertical lines are presented in the form of an inverted "L" figure, then the overestimation of the vertical relative to the horizontal is less than when they form a normal "L" figure. Piaget himself accounts for this effect in terms of greater frequency of eye movements and more attention being paid to the upper part of the visual field. Evidence that such attentional factors contribute to this bias comes from contemporary studies (Piaget, 1961; Gainotti & Tiacci, 1971): Dimensions of items on which gaze is mostly fixed are overvalued. In this context, the asymmetry of performance demonstrated by left-to-right readers who deviate leftward when bisecting horizontal line segments must be mentioned. Taking Piaget's and Gainotti and Tiacci's observations into account, the leftward bias could reflect either an underestimation of the right half of the line segment or an overestimation of the left half-line. As findings from Bartolomeo and Chokron (2001) seem to support the first possibility, an underestimation of the overall length of horizontal lines could be explained - and, consequently, account – at least partially – for the horizontal-vertical illusion as well. These observations make clear that other factors such as the angles of the lines, the format in which the lines are presented, and particularly whether the lines are shown in inverted-T or L-shaped formations must be taken into account as well (McKelvie, 1990).

The theory most commonly quoted to explain the horizontal-vertical illusion is the *frame theory*. It is based on the assumption that *differential context effects* serve to modulate the relative perception of stimuli oriented horizontally and vertically and, in doing so, serve to modulate the size of the horizontal-vertical illusion. It has long been known that the horizontal-vertical illusion is sensitive to the “frame” of the visual field around the target (Künnapas, 1955, 1957, 1959). Indeed, a strong case can be made that the tendency for verticals to appear longer than horizontals across a wide range of conditions reflects the intrinsic shape of the visual field, which is elliptical and wider than it is high (e.g. Prinzmetal & Gettleman, 1993). The typical explanation is now that length is perceived relative to this frame. A given vertical line occupies a greater proportion of the vertical field than a physically equivalent horizontal line occupies of the horizontal field. Thus, the vertical line encroaches on the upper and lower borders of the visual field to a greater extent than the horizontal line does on the left and right borders.

Another possible way to account for the dependence of the horizontal-vertical illusion on the shape of the visual field, namely in terms of differential context effects, was only recently put forward by Armstrong and Marks (1997). Because the visual field's width is greater than its height, people may tend to experience greater horizontal than vertical extents. With binocular viewing, the visual field is ovoid, its horizontal axis being approximately 0.5 times greater than its vertical axis, about 200^o versus 130^o (Prinzmetal & Gettleman, 1993). If, as a result of this asymmetry, people are exposed on average to greater horizontal than vertical extents, the long-term discrepancy in the distribution of horizontal and vertical perceptions might induce a differential effect on the perception of vertical and horizontal lengths, enhancing the former relative to the latter and thereby producing the horizontal-vertical illusion. Armstrong and Marks' theory is based on the findings of Caelli (1977) who had subjects compare the length of lines varying in shape (“squiggles”, sinewaves) and who inferred from the results that the horizontal-vertical illusion is related to interactions between “orientation detectors” in the visual system. In Caelli's view, the perception of length is tied directly to mechanisms that underlie discrimination of stimulus orientation. However, Armstrong and Marks suspect that differential effects of stimulus context operate at a level in the visual system beyond that of orientation detectors, much as the analogous effects in the perception of loudness arise in the auditory system beyond the level of the initiation of critical bands. In their view, the changes in perceived horizontal and vertical lengths constitute changes in the perceptual metric, i.e. compression and decompression of visual space. If so, the attenuation produced along a given spatial axis, whether horizontal or vertical, should be evident over the entire range of possible visual stimuli, not just over the range of stimuli used to induce it. According to Armstrong and Marks, these changes most likely take place in retinotopic coordinates, not in “external” space. “For, if a metric of perceived length were tied to distal rather than proximal stimuli, it should also depend on contextual distribution along other stimuli dimensions, such as wavelength compositions. But it does not.” (Marks, 1992 (p. 192)).

After all, however, even this quite elaborate theory does not comprehensively account for the illusion. Armstrong and Marks themselves had to accept that the illusion still persists when stimuli are presented within a frame that is equally wide and high, i.e. in the absence of a concurrent asymmetric visual frame. Furthermore, the illusory effect decreases with repeated trials – although it is still present after 20 trials (Kubi & Slotnick, 1993) – and intertrial feedback leads to a magnified decrease of the illusory effect (Brosvic & Cohen, 1988).

Even though rather rewarding – as demonstrated in the previous paragraphs – not all research that addresses the assessment of object proportions focuses on the phenomena of visual illusions. Several studies deal with fundamental principles of "normal" object proportion perception, i.e. how unambiguous objects are perceived in unambiguous environments. The following overview again mainly centers on the assessment of the dimensions of length, size and orientation which are relevant here.

Physical and Apparent Magnitude

One of the most consistent findings in visual perception is that with physical distance and size held constant, perceived size varies as a function of retinal eccentricity. Investigations concerning the extent and direction of the variations in the apparent size of an object, however, led to contradictory results. Helmholtz (1910/1962), who was, along with James (1890/1950) one of the first to systematically explore the nature of perceived size variations, noted, for example, that "if a long strip of paper, with parallel edges about three inches apart, is laid on top of the same table, it will be noticed, on looking at the middle of it, that by indirect vision it appears to be narrower at the ends than in the middle, and that it is apparently bounded by two arcs with their concavities towards each other" (p. 302). This simple observation suggests that as an object is moved out towards the periphery, its apparent size decreases. This, in turn, implies that in order for an object to maintain its apparent size, its objective size must increase as the object is moved into the periphery. The considerations – amongst others – led Helmholtz to construct the so-called "checkerboard illusion" (see Figure 2.7). If an enlarged version of this figure is viewed from such a distance that the two vertices on the vertical meridian just above and below the horizontal meridian subtend an angle of approximately 10^o, the curved lines appear straight and the apparent size of the resultant "squares" on the checkerboard appear approximately equal.

Stevens (1908), however, reported experiments in which the apparent sizes of peripheral objects do not agree with the observation of Helmholtz and the checkerboard illusion. He used simultaneous comparisons of a peripheral stimulus ("disk") with a fixed stimulus in foveal view. He found that, for most peripheral positions, a disk whose physical size was identical to that of the disk in the fovea appeared larger in the periphery. This is the opposite of what would be expected on the basis of the checkerboard illusion. He also found a considerable amount of variation in apparent size as a function of visual-field position with, for example, the same disk appearing, for one observer, larger in the right visual field, and smaller in the left visual field.

Optical factors may partly account for some of these results. As the checkerboard

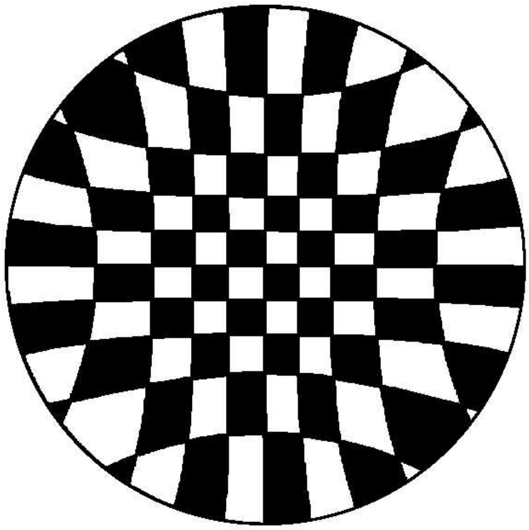


Figure 2.7: The checkerboard illusion (after Helmholtz, 1910/1962).

illusion is presented on a plane perpendicular to the observer's line of sight, strictly parallel lines on such a surface (the curved lines in the checkerboard illusion are hyperbolas) would subtend a smaller angle at the edge of the pattern than at its center. Hence, the lines would have to diverge slightly in order to maintain the same visual angle over the entire extent of the pattern. Another optical factor to be considered is that the retinal area corresponding to a constant visual angle varies in size as a function of retinal position. The reason for this is that the surface of the retina is not a true hemisphere with the nodal point of the lens at its center. Consequently, two objects subtending the same visual angle, but one imaged in the fovea and the other in the periphery, have different retinal sizes, with the size of the retinal image of the peripheral object being smaller since the periphery of the retina is closer to the nodal point than the fovea. In close relation to this factor, another structural explanation postulates that the decrease in perceived size can be attributed to the decrease in the density of receptors from the fovea to the periphery (e.g. Thompson & Fowler, 1980).

According to Helmholtz, neither of these optical factors is sufficient to explain the magnitude of the checkerboard illusion. Furthermore, they cannot explain why Stevens obtained effects which were in the opposite direction to those dictated by purely optical factors. Thus, other contributions have to be considered, such as pattern effects based on Gestalt theory (Carr, 1935/1966) or effects of attention, which will be discussed later in this chapter.

Literature on psychology contains several other reports stating that peripherally observed objects appear diminished in size (Salaman, 1929; Grindley, 1930; Collier, 1931; Fraisse et al., 1956; Piaget et al., 1959) as well as some attempting to explain visual illusions in terms of spatial anisotropies of the peripheral visual field (Pearce & Taylor, 1962; Richards & Miller, 1971). In spite of the frequent diminishment effect, there was no clear indication of either its magnitude or how magnitude varies with eccentricity. Stevens (1908) addressed these inter-dependences first, but, as he obtained inconclusive results (see above), could not formalise any relations. More recently, Newsome (1972) conducted studies to quantitatively explore the above-mentioned relations: Subjects matched the apparent size of a peripherally viewed object to a foveally viewed standard by adjusting the distance of the peripheral object (see Figure 2.8). This technique was applied before by Thouless (1931) and Joynson (1949), indicating that reliable measurements could indeed be obtained through peripheral viewing. However, it was argued that Newsome's procedure might cause artifacts due to background or contextual depth information. Furthermore, his studies yielded only sparse data as only one size of standard stimulus was employed, so that it was not possible to specify the extent of apparent size change for objects of different sizes. Later, Schneider (1978) provided data on exactly that dependence. He obtained magnitude estimates for the apparent length of line segments of various lengths and orientations at different eccentricities along the horizontal and vertical meridians. Results again showed that the apparent length of a line segment decreases as the line segment is moved away from the midline position into the periphery. Power functions adequately described the growth of line length so that equal-length contours could be derived.

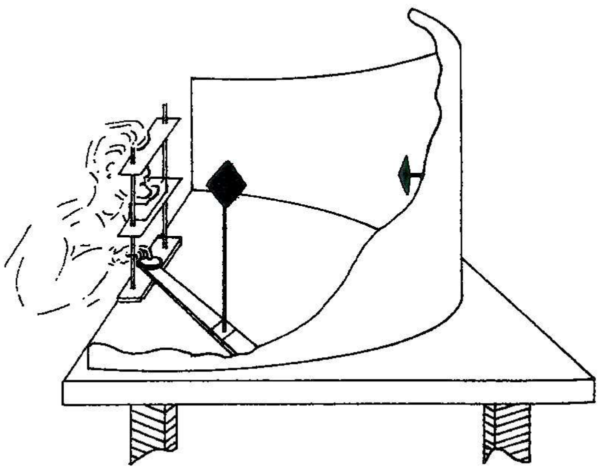


Figure 2.8: Apparatus used by Newsome (1972) to provide a simultaneous display of two stimulus squares with one stimulus adjustable in distance and eccentricity.

Psychophysical Scaling: Formal Relations between Physical and Apparent Magnitude

Indeed, in order to formalise the relation between discrimination and physical magnitude and that relation between apparent and physical magnitude, several different mathematical formulae could be thought to determine these correlations – not only regarding visual perception and such correlations with respect to line segments. Weber (1834) is credited with this idea and the terms "Weber law" and "Weber fraction" were subsequently coined, originally describing the correlation between apparent and physical weight. Even though Weber did not discuss the issue, it is evident that the relation could be a linear, logarithmic or power function – or some more complex function. From Weber's research on sensory thresholds Fechner (1860/1966) attempted to generalise the relation between stimulus intensity and sensation magnitude. He believed that sensations could not be directly measured, so he derived estimates of sensory magnitude from the measurement of difference thresholds. Fechner proposed a logarithmic function of the form

$$S = k \cdot log(I) \tag{2.1}$$

where S is sensation, k is a constant and I is physical intensity. This logarithmic function was widely accepted for over 80 years (e.g. Adrian & Matthews, 1927) and provided an impetus for the measurement of sensory processes. Although Fechner examined the discrimination of lifted weights, his research contributed more to the development of psychophysical methods than to the discovery of the sensory mechanisms involved in force perception (Boring, 1942). With the introduction of new techniques for scaling sensory magnitude, such as magnitude estimation, category ratings and ratio matching, several different psychophysical functions emerged. Stevens (1956, 1957, 1958) argued for a power law of the form

$$S = k \cdot I^n \tag{2.2}$$

(where n is the exponent of the power function) and maintained that this followed the underlying neural firing rate.

All functions that occur, however, seem to depend very much on the measurement technique and the different biases they produce (Poulton, 1989). There are also difficulties in how the physical stimulus is measured: Weights and lengths, for example, are measured on a linear scale, but sound intensity is measured on a logarithmic scale (decibels). Of course, the units of the scale have a profound influence on the resulting function (Weiss, 1981; Myers, 1982). The relation between stimulus intensity and the rate of neural firing is also controversial (Lipetz, 1971): Neural firing varies with the site at which it is measured (peripheral or more central), the state of adaptation, the sense modality, and many other factors. In some modalities, intensity is not coded by the rate of neural firing, but by the number of neurons recruited. Other modalities are more qualitative than quantitative. Thus, various authors have made a distinction between additive, prothetic or intensive dimensions (such as heaviness, loudness or brightness) and substitutive, metathetic or extensive dimensions (such as pitch and position). Stevens and Galanter (1957) claimed that the former produce subjective magnitude scales that can be fitted by power functions while the latter do not. It has also been claimed (e.g Stevens, 1939; Postman, 1946) that the former are suspectible to the time-order error (in which the second stimulus usually appears more intense than the first), while the latter are not. However, the distinction between the two is often blurred: Length of line segments, for example, gives a linear function rather than a power function (Poulton, 1989), but it is often described as a prothetic dimension (Pitz, 1965).

Thus, Stevens' (1975) hope of finding a clear resolution between stimulus intensity, the rate of neural firing and apparent intensity, seems in vain. If power functions are valid descriptors, the exponent of the power function can be used as a simple measure to describe the growth of the apparent magnitude in a given sensory domain. However, there is little agreement about unique exponents for the different modalities (Ross, 1997).

In fact, the construction of a psychophysical function is often not even clear within one sensory modality. A study regarding line length judgements – subjects judged the ratio of pairs of lines of different lengths – originally conducted by Engen (1971) demonstrates this. Whereas Engen claimed that subjective line length is a nonlinear function of physical line length and that it follows a power function, Bogartz (1979) challenged Engen's experimental procedure and showed that Engen's data indicates a linear function instead. This again was questioned by Fagot (1982), finally concluding that a psychophysical function cannot be constructed using either of the two previously proposed models.

After this excursion to the fundamentals of psychophysical scaling and the highlighting of considerable problems associated with the constructability of an appropriate psychophysical function for line judgements, let us resume the survey of studies dealing with processes involved in the visual perception of proportions and offering possible alternative explanations for the various observations.

Attention and the Assessment of Object Proportion

As mentioned before, *attention* is assumed to have a major effect on basic perceptual operations as well. This is true for both peripheral and foveal viewing. In this respect, Tsal's (1999) paper provides a good source for current findings, in particular concerning the effects of attention on visual localisation and length perception. In a recent study, Tsal and Shalev (1996) investigated how briefly presented vertical line segments are perceived. Here, the major comparison was between judgements of attended and unattended lines. Attention to line segments was achieved by presenting them at expected locations, whereas peripheral precuing was used to distract attention from the presentation position of the line segment and thus yielding the inattention condition. Results show that unattended line segments are perceived to be longer than attended ones and that attended judgements are more accurate for short line segments, unattended judgements more accurate for long ones. However, as Prinzmetal and Wilson (1997) suggested, the lengthening effect might be influenced by spatial interactions between the cue and the line segment. Studies of microgenesis (e.g. Nakatani, 1995) show that another important factor involved in length estimation is stimulus duration. Specifically, line length is underestimated in very brief presentations and is overestimated in longer presentations. This supports findings that Yokose et al. (1957) and Erlebacher and Sekuler (1974) obtained in earlier studies.

In order to explain the difference in representing an attended or an unattended (vertical) line, Tsal (1999) proposes the existence of different scales or metrics for estimating the length of attended and unattended line segments. The metric for unattended stimuli is composed of larger or rougher units, and the final output is mediated by rounding up processes, so that the unattended judgement is systematically longer than the attended one. Tsal thus introduces a concept of "attentional receptive fields" (ARFs) whose sizes reflect these metric properties and concludes that ARFs are an appropriate concept at least for distinguishing between coarse unattended and fine attended perception. Results from Bachmann and Kahusk's (1997) microgenesis studies regarding differential effects of attention on fine-quantitised and coarse-quantitised images seem to be consistent with the concept of ARFs.

In additional studies, Tsal subsequently tried to apply the ARF hypothesis to visual localisation tasks, again assessing the effects of attention and inattention. His prediction that unattended stimuli can only be coarsely localised whereas a finer localisation of attended stimuli can be achieved, was supported (Tsal & Bareket, 1999; Tsal & Bareket, 2001). The results of the two localisation studies clearly showed that attention improves the localisation of stimuli in the visual field. Furthermore, the results are in line with previous studies that demonstrated significant effects of attention on localisation (Butler, 1980; Egyl & Homa, 1984; Müller & Rabbit, 1989), and are inconsistent with the notion that localisation is a completely preattentive operation (e.g. Sagi & Julesz, 1985).

Taking into account findings from neuropsychological investigations, several other authors support this view. Van der Heijden (1992, 1993, 1996), Müsseler (1987), Müsseler and Neumann (1992) and Müsseler and Aschersleben (1998) quote the "position-as-a-code-for-position" assumption, which states that the topographic location of an object in the outer world is represented geometrically by the location of a set of neurons in a topographic map in the brain (cf. Smythies, 1994). One of the major theoretical problems the assumption introduces is, for example, that even the best topographic map in the visual cortex, V1, is not geometrically congruent with the topography in the visual field. Thus, purely neurological processes based on the anatomy of retinal or cortical maps could hardly encode positional information alone. Instead, van der Heijden et al. (1999) conducted partial-report bar-probe studies that again suggest that visual selective attention is closely connected with visual perception of position. According to those authors, the calculation of perceived position involves two processes, a globally and a locally operating one: Globally, the spatial position in the visual field is coded in terms of eye movements, the local operation has more in common with processing identity rather than position. Similar views can be found in Wolff (1987) and Koenderink (1990) or, earlier, in Poincaré (1902, 1905), Helmholtz (1910/1962) and Taylor (1975).

A "receptive field approach", similar to the idea of ARFs from Tsal (1999), was advanced by Bacon and King-Smith (1977), describing line (feature) detection processes. This idea was inspired by Hubel and Wiesel's (1962, 1968) demonstration that cortical neurons in the cat and monkey respond strongly only to visual stimuli (e.g. lines and edges) of a specific orientation. Subsequent attempts followed to analyse human psychophysical data in terms of "subunits, "channels" or "detectors" and established similar properties, for example Campbell and Kulikowski (1966) and Blakemore and Nachmias (1971) regarding orientation-specific masking and adaptation effects or Andrews (1967a, 1967b) regarding the error in orientation judgements of straight line segments. Bacon and King-Smith now assumed in their psychophysical study that independent "subunits" – similar to the simple cells of the visual cortex that have long narrow receptive fields and are strongly excited by lines oriented along their long axis – contribute, by probability summation, to the detection of a line. If a line segment is shorter than the subunit length, then extending the line length will increase the sensitivity of all the subunits affected by the line, and a relatively large increase in visual sensitivity will occur, corresponding to this "physiological summation" within subunits. However, for a line segment which is substantially longer than the subunit length, the main effect of extending line length is to stimulate more subunits, resulting in a relatively small increase in sensitivity owing to probability summation. The performance of Bacon and King-Smith's proposed quantitative model to estimate the subunit length is in good agreement with Andrews' (1967b) analysis of orientation sensitivity. However, it by no means explains all their data. It was shown, for example, that the ability of a subject to judge the orientation of a broken line as compared with a continuous line is poorer than expected from considering the contribution of the missing section. This could be due to inhibitory and facilitatory interactions between subunits which were not accounted for by the model.

A "Classical" Psychophysical Measure: Reaction Time

Apart from the relevant aspects regarding line perception mentioned already, such as eccentricity, position, alignment, length, orientation, psychophysical method of presentation, task effect and the influence of visual illusions, "conventional" measures such as reaction time (RT) were analysed as well. Papers by Link and Tindall (1970, 1971) present an extension to Henmon's (1908) finding that RT decreases as the difficulty of discriminating the difference between two line segments decreases – results Birren and Botwinick (1955) and Botwinick et al. (1958) obtained as well. By imposing a maximum RT limit (known to subjects), Link and Tindall demonstrate that RT remains constant with respect to changes in discrimination difficulty, but that the correct response probability increases with increasing difference between two line segments. This questions the validity of the assumption that a speed-accuracy trade-off results from a binary mixture of two RT distributions associated with detection and guessing performance (cf. Atkinson, 1963; Luce, 1963; Ollman, 1966; Yellot, 1967), two modes of operation subjects obviously choose between given such a task. Link and Tindall presume that with an RT deadline the temporal process controlling RT imposes limitations on the amount of information fed into the decision process, so that the temporal process dominates the decision process.

Rather than investigating discrimination tasks, Hartley (1977, 1981) considered RT an essential variable in attempting to understand the processes involved in perceptual magnitude estimation. He observed that RT increases systematically with judged magnitude of a comparison in relation to a standard line – an observation Sekuler and Nash (1972), Bundesen and Larsen (1975), Larsen and Bundesen (1978) and Uhlarik et al. (1980) made for size judgements as well. Encouraged by his subjects' reports that they laid off a mental model along the line to be estimated, Hartley proposed an image-based mental measurement model. Indeed, the model was consistent with the linear relation between the time required to make a magnitude estimation and the value of the estimate itself. These results suggest that RT depends on the number of times the standard was mentally laid off against the comparison.

A study by Kerst and Howard (1983), however, challenged Hartley's image-based mental measurement model. In an experiment where subjects made magnitude estimates of the loudness of a tone preceded by a standard, the relationship between RT and judged magnitude held as well. As the effect is obviously not restricted to spatial judgements but occurs in the non-spatial continuum of loudness as well, a visual imagery explanation should be revised as it might be too specific to account for an RT effect in the general case. Kerst and Howard therefore suggest a more general, sensory model – based on Hartley's proposal – that lays off sensory representations, i.e. visual codes in the spatial, length estimation case, and auditory codes in the intensive, loudness case (cf. Krantz, 1972).

In summary, the findings of numerous studies investigating the visual perception of proportions – and that of line segments in particular – indicate a strong influence of attention. Taking this into account, it is striking that only few authors considered the measurement of eye movements a useful instrument to validate their assumptions and explanatory approaches. As has been shown in Sections 1.1 and 1.2, eye movements yield data on the locations and the temporal order of the acquisition of visual information, which then reveals the distribution and dynamics of visual attention.

2.3 New Insights through Eye Movements

Ikeda et al. (1977) are among the authors who conducted studies that relate eye movements to line perception. They were particularly interested in the influence of the visual field size upon acuity in comparing lengths of two line segments. Using a gaze-contingent stimulus presentation method, only a portion of the two horizontally arranged line segments was visible at a time. The position of the visible portion was controlled by the subject's eye movements so that the fixation point coincided with the center of that portion. When the visual field, i.e. the visible portion, was narrowed to and below a size that approximately equaled one of the lines' length, the comparison acuity dropped rapidly. The authors thus concluded that very accurate length comparisons (cf. Pollock& Chapanis, 1952; Le Grand, 1967) are only possible when the whole line segment can be observed at one time and – obviously essential – peripheral information is available. Ikeda et al. seek support for these conclusions from findings in size perception: When comparing the size of two squares, often no fixation points fall on edges of the squares (Buchsbaum, 1972), which presumably would have occurred if the fovea was used exclusively.

However, Ikeda et al.'s study is controversial insofar as line length was not systematically varied and results should consequently not be generalised. Even more important, it must be criticised that the authors do not consider the possibility that, in line comparison, peripheral information might be used to generate new fixation points for subsequent foveal processing rather than contribute to length estimates directly. In that case, line perception could in fact involve different mechanisms than size perception. Controlling the size of the visual field may thus not be appropriate because results could not be transferred to normal viewing conditions for generalisation purposes.

A diverse range of studies addressed the effects of multiple eye fixations on the perception of visual attributes with particular emphasis on memory for these attributes. Some of these studies have involved the integration of information from eye fixation to eye fixation (trans-saccadic integration), either in general or within a more narrowly defined domain such as direction constancy across saccades. In integration paradigms, a pair of (more or less complex) displays is presented sequentially and subjects must integrate the two displays to perform a task. Within such a paradigm, various authors, for example DiLollo (1977), Sun and Irwin (1987) and Irwin and Brown (1988), showed that, when complex patterns are viewed, eye movements interfere with visual memory and/or integration: When subjects move their eyes between the presentation of the two displays, visual memory does not persist in such a way as it does without eye movements (Irwin et al., 1983; O'Regan & Lévy-Schoen, 1983; Rayner & Pollatsek, 1983). Instead of integrating two displays, Irwin et al.'s (1990) and Irwin's (1991) follow-up studies required a same-different judgement of the two displays (cf. Phillips, 1974). When this was done across eye movements, performance was above chance, indicating that some memory survived. But, performance was much worse than that observed without eye movements, which again indicates that eye movements interfere with memory. This, however, is not always the case.

Studies of visual direction constancy, i.e. the ability to judge the position of objects accurately despite changes in eye position, have shown that there is essentially no interference from eye movements with memory (e.g. O'Regan, 1984; Hansen & Skavenski, 1985; Matin, 1986). Using other paradigms, it has been shown that, for example, eye movements facilitate shape-recognition tasks (Schlingensiepen et al., 1986; Hayhoe et al., 1991), which provide at least indirect "evidence" for some memory surviving interference with eye movements. In an attempt to provide a more systematic way to measure the degree of interference due to eye movements, a study by Palmer and Ames (1992) quantified the degree of interference for a variety of stimuli and also attempted to isolate memory limitations from other performance limitations. Several experiments illustrated that size and shape attributes were remembered from previous fixations for several procedural variations with little or no interference. According to the authors, this finding is consistent with the "hypothesis that no very short term visual store survives eye movements. Instead, information must be recoded into some kind of limited-capacity memory to survive from eye fixation to eye fixation" (p. 296).

The overview of research in this and the previous sections – although only a fraction of studies in this field could be reviewed – makes clear that a large number of phenomena, often very special cases, exist which were investigated regarding many aspects of the perception of object proportions. Furthermore, it appears that there is no single comprehensive, consistent explanation or theory to account for the various observations. Researchers approached the questions of, for example, how line segment length or object size are visually processed from various directions. They advanced specific theories and models based on psychological, psychophysical as well as physiological and neurophysical explanations. It is evident that all these factors contribute to the perception process; however, it is not clear yet to what extent, and how, they interact. Even though it is frequently claimed that the study of visual illusions is capable of revealing the principles governing non-illusory visual perception as well, it can be questioned if the rather particular stimuli and experimental conditions involved do not interfere with the visual perception processes. Results should therefore be carefully reviewed before being used to explain "normal" vision mechanisms as they might otherwise lead to blurred "evidence".

Criticism could also be made with respect to the often very elaborate and sophisticated psychophysical methods applied. Apart from task effects which are shown to easily lead to complete inversions of results, the conclusions drawn from indirect measurement methods are at least not undisputed. Results from different studies sometimes appear to be contradictory and can be difficult to integrate. Partly due to this, many of the theories put forward are often not capable of explaining the underlying perception mechanisms and their functions. It appears that (some or maybe even all) the relevant parts of the "puzzle" have been identified, but that we still have to understand how they actually function and, later still, how to put them together.

2.4 Hypotheses

From the findings presented, it appears to be both sensible and promising to further pursue an eye-movement approach to learn more about the principles underlying the visual perception of object proportions. In particular the perception of *line segments* as a prototypical example for a basic and abstract stimulus under normal viewing conditions should be ideal to provide insight into these fundamental perception processes. The decision to further explore line segments has also answered the so far open question regarding the *stimulus dimension* (see Section 2.1). Due to high costs of the eye-tracking device and only recent advances in technology, the opportunities this paradigm offers have not been sufficiently explored so far. Data from eye-tracking experiments provides very detailed spatio-temporal information on the distribution of attention, which is directly accessible and highly relevant in this context.

It might now be possible to advance some *hypotheses* about the perception processes in the proposed scenario while following the fundamental cognitive structure for the solution of (visual) comparison tasks.

The first (cognitive) step that has to be accomplished when comparing two line segments A and B is the *assessment* of the "target" line segment A. As line segments have a certain one-dimensional "extent", namely their length, it is possible that the entire line segment cannot be assessed *holistically* with one look. Instead the gaze may have to shift across the line segment in an attempt to *analyse* the line segments and its relevant attributes.

What could be possible candidates that attract attention and thus initiate these shifts of attention? The *end points* of a line segment probably yield such attractor or "landmark" points. This could suggest that a line segment is *decomposed*: Key locations are foveally scanned, relevant information perceived at several of such locations and then *fused* or *integrated* to yield the originally intended assessment. More specifically, it can be hypothesised that for the analysis of characteristic attributes of lines segments, in particular their length or orientation, the assessment accuracy of such attractor locations plays an important role. Length assessment would thus be decomposed into the *location* *assessment* of the two end points and the "computation" of the *distance* between these perceived locations to yield the line segment length. However, it is not clear if one end point has to be *foveally* observed, i.e. fixated, while the other is only *peripherally* assessed. Alternatively, the *distance* between the two end points could be *visually measured* by a saccade when attention shifts between the two end points. Both mechanisms should yield the length of the line segment.

Not only in case the first, "peripheral" strategy is pursued, it might be worth to *investigate location, length and orientation assessment in "eccentricity experiments"*. Findings from these experiments might also contribute to the further exploration of the visual measurement strategy: *Saccade planning* is known to be a process mainly guided by peripheral visual perception and could thus also benefit from knowledge about the accuracy of peripheral location assessment. The accuracy of location assessment might thus also influence the accuracy of measuring saccades.

The previous consideration are also relevant for the next cognitive processing step, namely the *memorisation* of an attribute of a line segment. Length could thus be *mentally represented* as *saccade length* or as the *distance between a fixated and a peripherally perceived end point of a line segment*. On appearance of the "comparison" line segment B, the visual *assessment* has to be repeated, the previously memorised representation of A *recalled and mentally compared* to that of B. Depending on various factors this could be easy of difficult. If stimuli are, for example, shown *sequentially* one after the other, line segment A cannot be re-assessed by *shifting attention back* to the respective line segment – it is not visible any longer. This, in contrast, could happen in a *simultaneous* comparison scenario where A and B are presented side by side. Let us, for example, assume that the subjects' task is to state which of the two line segments is longer. If the representation of one of the line segments or their relevant attributes is not accurate enough to accomplish this task attention, i.e. gaze, can shift back to that stimulus. This will "update" and preferably *improve* the mental representation. Depending on the lengths differences between the two stimuli (*"discrimination difficulty"*) in such a scenario the above-mentioned *holistic* or *analytic* processing modes might be applied, manifested in corresponding eye-movement patterns.

The following investigations will attempt to test these hypotheses and validate the proposed processing mechanisms. The analysis of eye movements in particular should provide insight into the perceptual processes of the specific comparison task of line segment assessment. If the empirical data supports the hypotheses, this can further be understood to yield support for an adequate representation of the different steps of the cognitive structure. This would finally present the opportunity to build a model that computationally implements the perception mechanisms in an attempt to reproduce the empirical data.

The next chapter discusses in detail the methodological preliminaries such as stimuli, experimental design and chosen setup. The chapter starts with a comprehensive description of the eye-tracking laboratory at the University of Bielefeld and presents the technical details of the SMI EyeLink eye-tracking system.

Chapter 3

Methodological Preliminaries

3.1 Eye-Tracking Laboratory

The comparison of various eye-tracking techniques demonstrated that not all of them are equally suitable for reliable and accurate measurement of eye movements (see Section 1.4). Furthermore, most techniques do not provide natural conditions for subjects during experiments. They severely restrict the freedom of movement, require the wearing of uncomfortable tracking devices and include lengthy setup and calibration procedures. These artificial conditions easily produce data artifacts and can therefore yield incorrect conclusions on visual processes. The SMI EyeLink eye-tracking system (see Figure 3.1) that was used for all experiments reported here overcomes the above-mentioned restrictions.

Figure 3.1: The eye-tracking laboratory of the Neuroinformatics Group at the University of Bielefeld.

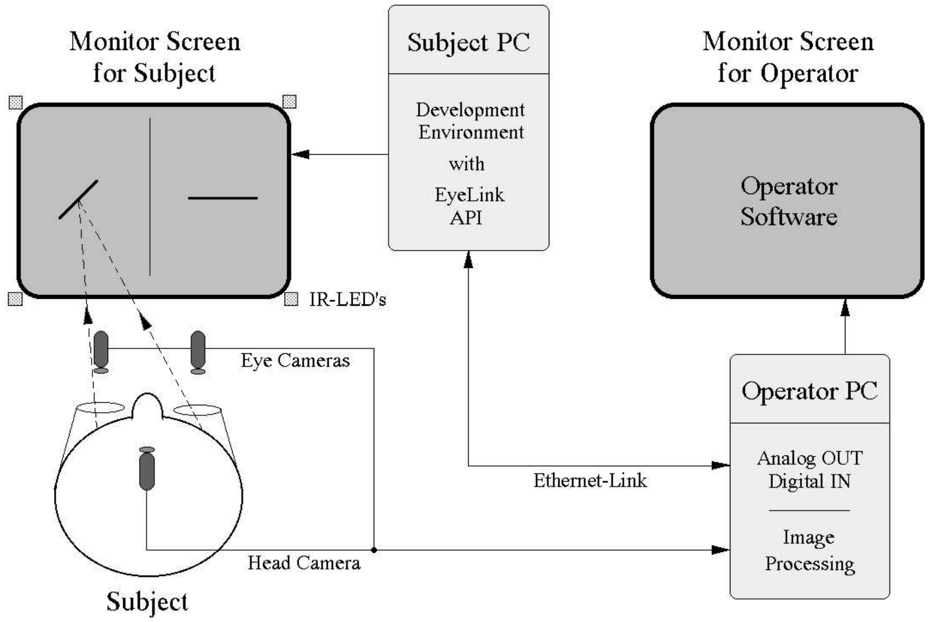


Figure 3.2: Scheme of the SMI EyeLink system.

Basically, the EyeLink system consists of three components: The *eye-tracker headset*, a so-called *Operator PC* and a *Subject PC*. Figure 3.2 schematically shows the system setup and cabling.

Eye-tracker Headset

The main component of the EyeLink system is the eye-tracker headset (see Figure 1.14) as already discussed in detail in Section 1.4. In summary, the headset consists of two IR cameras that yield images of the eyes and enable binocular eye tracking. An additional camera which is necessary for monitoring the head position observes four IR LEDs attached to the corners of the stimulus display. Data from the three cameras is transmitted to an image processing interface that computes the gaze positions in stimulus display coordinates, incorporating head movement compensation. In order to obtain reliable data, the exact adjustment of the cameras and the execution of a calibration procedure are necessary. The following paragraph provides an overview of the system's specifications:

Sampling rate: 250 Hz temporal resolution for both pupil tracking and head movement compensation.

Eye position tracking range: $\pm 30^o$ horizontally and $\pm 20^o$ vertically, depending on system setup.

Gaze position tracking range: More than $\pm 20^o$ horizontally and $\pm 17^o$ vertically with moderate head motion. Head tracking is used to compute eye-rotation angles and gaze-position resolution (effective screen distance) in real-time. Head-position data is not available as output data.

Gaze and eye position resolution: 0.005^o (20 seconds of arc), noise level (standard deviation): 0.01^o. This allows for an unfiltered velocity level of better than 3^o/sec.

Gaze position accuracy: 0.5^o–1.0^o average error, measured by calibration-accuracy validation. This accuracy is primarily limited by fixation accuracy of the subject during calibration. Accuracy is reduced during large head movements (greater than $\pm 15^o$) due to calibration extrapolation.

Pupil size resolution: 0.1% (0.01 mm change in diameter reliably detectable). Pupil size noise level of 0.003 mm rms.

Working distance: 4–7 cm camera-to-eye distance. 40–140 cm display-to-eye working range. However, the display-to-eye working range can be extended to up to 400 cm when using a set of IR screen-markers with higher luminance.

Headset weight: 600g, which means a reduction of 50% compared to the previously used OMNITRACK1 headset.

Eye illumination: 2 IR LEDs per eye, wavelength: 940 nm. Irradiance at eye: Typical 0.8 mW/cm^2, maximum 1.2 mW/cm^2.

Online eye-movement parser: Detection and analysis of saccades, fixations and blinks in real-time. Saccades of 0.5^o or less are reliably detected.

Operator PC

The Operator PC is a PC compatible computer – Pentium I/166MHz – with MS-DOS 6.2 and MS-Windows 3.11 and the following EyeLink-specific components installed:

- High-speed eye-tracking hardware
- Ethernet card
- EyeLink eye-tracking software
- EyeLink analog and digital I/O card
- File viewing and analysis tools

This PC performs real-time eye tracking at 250 samples per second during operation so that the true gaze positions on the subject display (*sample* data) are made available every 4 ms. Sample data can be transmitted to either a standard built-in or a customised online detection analysis of eye-motion events such as saccades and fixations (*event* data). Sample or event data (or both) can be stored in a data file on the Operator PC, sent through the Ethernet link to the Subject PC or output as analog signals. All data is stored along with a time stamp which enables easy synchronisation of eye-movement data with, for example, stimulus presentation times or response button events. Data sent through the Ethernet link is available to the Subject PC only about 6 ms after an event occurs. Due to this short transmission latency, data can be used to control the stimulus display online (see below).

The experiments are monitored from the Operator PC. All relevant information is displayed on a 17" computer monitor screen and only visible to the operator, not to subjects. The operator performs subject setup, monitors performance and can control applications running on the Subject PC. Various EyeLink software menus allow the operator to select options such as "Camera Adjustment" or "Calibration" and adjust corresponding parameters such as "Pupil size threshold" or "Calibration sequence type". This is performed in the pre-experimental subject setup.

During an experiment, the Operator PC monitor screen shows a simplified representation of the scene on the Subject PC and a superimposed marker indicating the current gaze position of the subject. This enables the operator to monitor eye movements during recording. The operator can thus decide online whether setup changes or recalibration is necessary in order to achieve more accurate measurements.

Subject PC

The Subject PC is a PC compatible computer – AMD K7/600MHz – with MS-DOS 6.2 and MS-Windows '98 and the following components installed:

- Ethernet card
- EyeLink communication drivers and applications
- File viewing and analysis tools

Applications running on this PC provide subject displays for experiments and calibration targets during eye-tracker calibrations. All stimuli are presented to subjects on a 20" Sony MultiScan 20sf II computer monitor screen. A calibration procedure has to be performed prior to every experiment (see Section 1.4 for details).

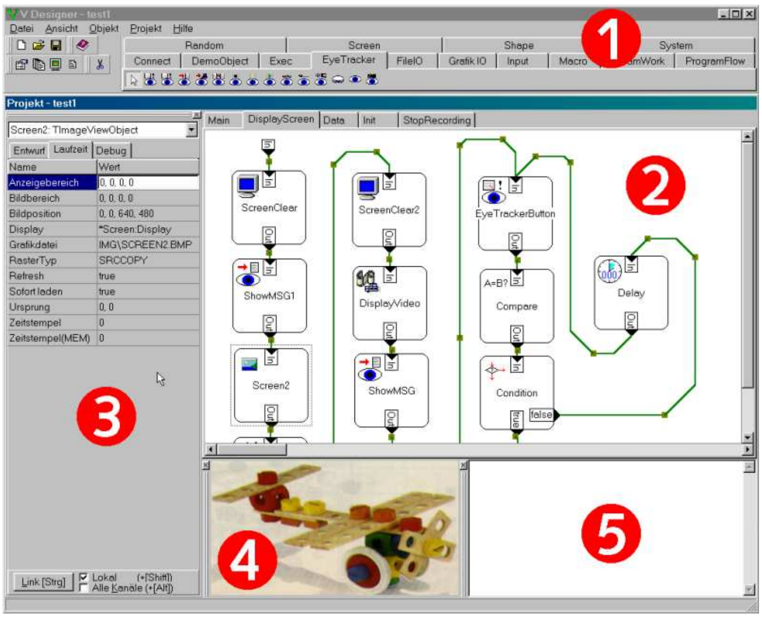
During the experiment, a control programme determines how the experiment proceeds, for example, which stimuli are presented and when button responses are required. Most experiments reported here use custom-made C(++) control programs run under MS-DOS. Only recently, the so-called *VDesigner* was developed (Clermont, 2001; Koesling, Clermont & Ritter, 2001). The VDesigner is an MS Windows-based programming environment for psychological experiments and was used for the Experiments S1 and S2.

The VDesigner Visual Programming Environment

So far, the design and implementation of eye-tracking experiments demanded an in-depth knowledge of technical aspects of the hard- and software employed. However, often scientists with little or no programming experience are involved. To address these requirements, the *visual programming language "V"* and the *visual programming environment "VDesigner"* were implemented for a *user-friendly* realisation of psychological experiments, incorporating an eye-tracker system.

Visual programming techniques present a promising approach to the efficient development of software prototypes. They enable programmers to generate computer programs by *intuitively* "drawing" diagrams rather than by typing in command sequences as in conventional textual programming languages. Existing experimental environments in general, for example ERTS (Beringer, 1994) or PESt (Duwe & Claußen, 1995), and those for eye-tracking experiments in particular, such as KODAVA (Pomplun, 1994) or CLAFIEE (Becker, 1998), are based on textual programming and show the common restrictions of this concept, in particular concerning usability and versatility.

The VDesigner's visual programming concept allows the user to select *objects* from a menu, place them on the *workspace* and *connect* them by drawing line segments so that the established route determines the *processing order* (see Figure 3.3). Objects represent specific *functions*, for example "eye-tracker calibration" or "show box" and carry parameters that can be adjusted to specific requirements via drop-down menus. Objects are available in various *classes* according to their functionality, for example "eye tracker" or "graphics display". An *on-line help* provides support for users.



❶ Object pool

❷ Project view

❸ Object inspector

❹ Preview window

❺ Message window

Figure 3.3: Screenshot of the VDesigner programming environment for eye-tracking experiments.

The VDesigner is Microsoft-Windows based, so that, for example, standard Windows hard- and software interfaces are accessible. The VDesigner supports *multimedia applications* such as hypertext page or video and sound presentation, often needed in eye-tracking experiments. Since timing is known to be critical in Windows environments, an independent timing function was implemented which gives a highly accurate account of run-time behaviour. Extensive research and testing has shown that the system's temporal behaviour is absolutely *uncritical*, essential in eye-tracking research.

Furthermore, the VDesigner was implemented as an *open* system and can be adapted to specific demands. The object-oriented philosophy of the visual programming language V allows to *enhance* the system's functionality by programming new objects. This can be realised via a C++ interface. A so-called "ObjectHelpWorkshop" was implemented to assist programmers with the generation of on-line help for new objects. Altogether, the VDesigner can be considered an extremely versatile development environment for eye-tracking experiments. It supplies programmers with a user-friendly graphical interface for rapid experiment development in a wide field of eye-movement research (and beyond).

Both the C(++) and VDesigner control programs use the EyeLink software libraries or DLLs (*D*ynamic *L*ink *L*ibraries) for communication with the Operator PC via the Ethernet link. As already mentioned, eye and gaze positions for example can be received from the Operator PC online and in real time via this link. This allows for a *gaze contingent* stimulus presentation on the Subject PC screen which opens new horizons to both experiments and applications:

- It is now possible to design experiments where stimulus visibility is restricted to a designated area around the actual gaze position – important with regard to the effect of peripheral vision on visual guidance, for example, in visual search tasks (Pomplun et al., 2001) (see Figure 3.4, left).

- Possible applications now include gaze controlled computer interfaces – particularly useful as communication or interaction devices in natural or virtual environments for physically handicapped individuals (see Figure 3.4, right).

All in all, the EyeLink configuration provides a convenient basis for eye tracking research in view of the planned experiments. Flexible programming interfaces are provided to ensure that all desired stimuli can be presented as intended. Maybe even more important, the technical equipment with its high-resolution tracking device and gaze data available online enables us to access and record the eye-movement and gaze-trajectory data required for a reliable statistical analysis.

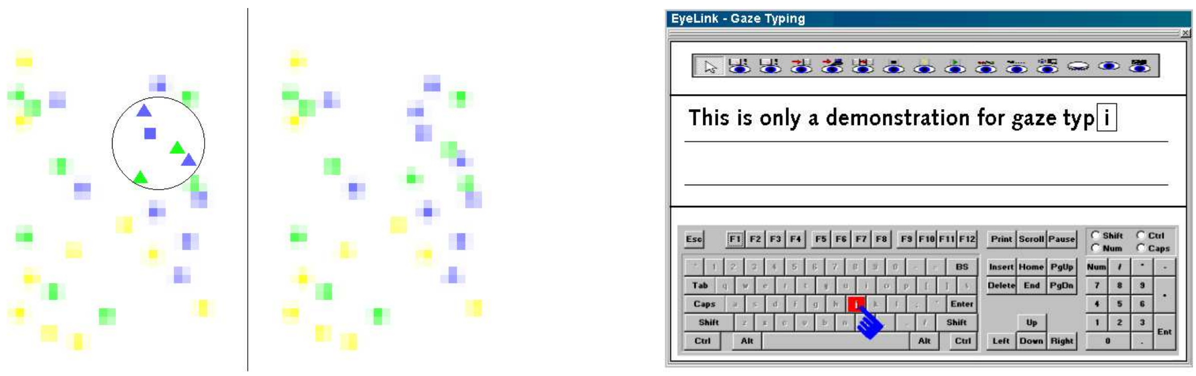


Figure 3.4: Left: Possible stimulus display in a gaze contingent visual search task. Right: Gaze controlled keyboard for human-human or human-machine interaction.

3.2 Stimuli

Exploring the theoretical background of the perception of object proportions in Chapter 2 and reviewing the capabilities of the technical eye-tracking equipment available has partly cleared the way for the current research. The findings of Chapter 2 render an eye-movement approach promising for learning more about the principles underlying the visual perception of object proportions in comparison tasks. The spatio-temporal data from eye-tracking experiments should make a valuable contribution to better understand the attention processes which seem to play an important role here. From a technological point of view, the EyeLink eye-tracking system provides an ideal basis for presenting a wide range of individual stimuli and accurately monitoring and recording subjects' eye movements. Next, the stimuli that will be used have to be defined and the experimental task(s) established.

The choice of stimuli and procedure are essential preliminaries that must be made carefully, as the combination of these two determines whether or not the subsequent analysis of experimental data yields interesting information on the intended relationships. In this context, the definition of independent and dependent variables is also very important. So, what exactly do we want to investigate, which stimuli seem appropriate for this investigation and by which means and following which strategy can we obtain the desired results? The following paragraphs address these questions.

3.2.1 Choice of Stimuli

Depending on the type of stimulus to be assessed, the perception of its proportions obviously takes place in one particular dimension or a combination of various sensory dimensions. Usually, either tactile, auditory, olfactory or visual sensors are stimulated by the stimuli's basic physical quantities of length, orientation, mass and time and other quantities such as weight, density, rate, force or energy. In the present context, the visual perception of stimuli and some of their relevant attributes will be investigated.

As concluded from Chapter 2, the visual perception of line segments emerged to be of particular interest for exploration within a visual comparison paradigm. Line segments represent very basic and abstract stimuli. Furthermore, if presented in isolation, it should be possible to eliminate perceptual interference from high-level factors, such as context and figural or Gestalt-based aspects, i.e. semantic content. Due to the simplicity of line segments – and when presented in an uncluttered environment – these stimuli should be ideal to provide insight into fundamental perception processes under normal viewing conditions. So, what exactly should line segments look like, which dimensions seem promising for systematic variation, and which levels of variation make sense?

3.2.2 Selection and Variation of Stimulus Dimensions

According to the NRICH Online Mathematics Thesaurus of the University of Cambridge, UK (http://www.thesaurus.maths.org), a line in a mathematical sense is defined as "an element of geometry that has only one dimension, its [infinite] length. It has no breadth or

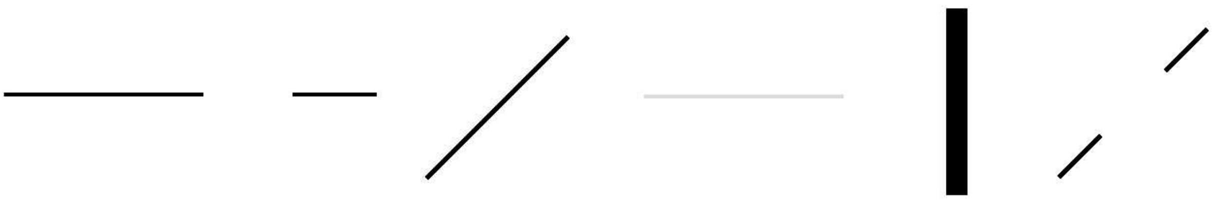


Figure 3.5: "Standard" line segment (left) and variations of relevant line segment dimensions (from left to right): Length, orientation, colour/contrast, breadth/width, continuity.

width and is often thought of as a set of points that are so very closely set down that there are no gaps between them. A line segment is usually part of a straight line between two given points on it. There are many different types of line segments. They can be diagonal, horizontal, vertical, oblique, parallel, perpendicular". According to this definition, a line segment is mainly determined by its *length* (with regard to a standard measure) and its *orientation* (with regard to the horizontal, i.e. 0^o *tilt*).

Several other visual attributes also determine the appearance of line segments. Figure 3.5 shows a "standard" line segment and illustrates a number of possible dimensions of line segments that can be varied and may be expected to greatly influence visual processing. Apart from the already mentioned length and orientation dimensions these can be, for example: The line segment's *colour or contrast* towards the presentation background, the line segment's *breadth or width* (although this is not in accordance with the definition quoted above) and its *continuity.* In detail, these factors could have the following possible impacts on visual perception processes (see also Chapter 2):

Length: The most basic dimension of a line segment, namely its length, is an obvious candidate for variation. In fact, varying this dimension seems promising when it is done in such a way that the presented lengths of the line segments coincide with the extent of either foveal, parafoveal or peripheral visual processing ranges. Depending on length, distinct processing strategies for the different ranges might be applied, possibly manifested in distinct eye-movement patterns or gaze trajectories. An assumption could, for example, constitute the summation of length across several saccades for "long" line segments. This aggregation could then lead to a less accurate assessment of overall length in comparison with a comprehensive, one-fixation, foveal assessment of a "short" line.
N.B.: It can be argued whether absolute or relative assessment accuracy ("error") is the "better" measure. Either choice could invert results of the other so that "good" relative accordance might turn into "poor" absolute accordance (and vice versa). Particular care should consequently be taken when error measures are quoted to judge assessment performance. This problem will be discussed again later.

Orientation: Orientation is another basic dimension that affects the perception of (the length of) line segments. In particular, the interactions between orientation and perceived line segment length are well known in visual illusions and under normal viewing conditions, although explanations are not very consistent (see Section 2.2).

Assuming that attention plays an important role in length perception, variations in shifts of attention (manifested in eye-movement patterns) for different line segment orientations could help to explain differences in length assessment accuracy. This, in return, might then facilitate the understanding of orientation-induced phenomena as present in visual illusions. Line segment orientation variation from horizontal, through oblique to vertical should consequently be investigated.

Colour/Contrast: The colour of line segments and the contrast between line segment and background should be of some significance, in particular with regard to attention processes involved in the perception of length. Furthermore, this should be the case regardless of the specific procedure or psychophysical task, for example direct or sequential comparison, discrimination or target matching. Less salient colours or a less pronounced contrast, i.e. line segments that do not “pop out”, should result in a need to more closely visually inspect the line segment attributes that are relevant for the dimension to be assessed. Alternatively, if this attention is not increased, a deterioration in assessment accuracy could emerge.

Breadth/Width: Depending on the ratio of the width of a line segment to its length, two different consequences for the length perception processes are possible. If the line is only slightly increased in width, this could have a similar effect to choosing a “pop out” colour or a high contrast: Assessment of length is facilitated, peripheral information is easier to integrate and less direct attention has to be paid to the line segment attributes relevant for length assessment. In case the width of a line segment is increased to such an extent that it will rather be perceived as a two-dimensional object, other factors related to shape processing and the assessment of size rather than length could influence the attention processes. An investigation of these attributes appears to be rather rewarding, however, mechanisms concerned with size perception and Gestalt principles will have to be considered here as well.

Continuity: In the extreme case of reduced continuity, a line segment would be determined by its end points alone. This, however, could imply a distance rather than constitute a line segment length. Yet again, if we consider a continuous line segment to denote the distance between two points – namely the line segment’s end points – the notions of length and distance become equivalent and inter-changeable. It is not clear how variations in continuity interact with other stimulus factors. A naïve assumption would be that the presentation of the end points of a line segment does not affect length (distance) assessment. It might even facilitate it because essential information (and only that) is available. Regarding orientation assessment of such a line segment, no facilitatory effect should (naïvely) be expected: Orientation has to be calculated indirectly from the relative positions of the two end points to each other, which would rather complicate orientation assessment and therefore make it more susceptible to (greater) error.

The variety of factors, their possible interactions and their impacts on the perception processes involved in the assessment of line segment lengths (in particular) provides great scope for promising visual comparison experiments. As we will see later, only a selection of those factors can indeed be reviewed: Even when such a limitation is imposed, the possible observations become very numerous and yield rather complex interactions that have to be analysed. But, which tasks and which strategy determining the course of consecutive experiments would be most sensible now? The following section shows the available options and aims to motivate the chosen procedure(s).

3.3 Procedure

The overview of previous research concerned with visual comparisons and the assessment of object proportions revealed a great variety of possible experimental settings and procedures the authors employed to address specific questions and hypotheses (see Chapter 2). Depending on the investigated phenomena and the intended conclusions, some of the chosen psychophysical methods and procedures seem more suitable than others. However, criticism of and dispute over the chosen procedures and those that would have been preferable are common and widespread.

3.3.1 General Experimental Proceeding

Again, the objective of the research presented in the thesis at hand is to find out more about how attention processes, manifested in eye-movement patterns and gaze-trajectories and, of course, "conventional" psychophysical data, contribute to the perception of object proportions. Based on previous studies, the investigation of the main attributes of line segments such as length and orientation in a visual comparison scenario was rendered most rewarding in this respect. Following the fundamental cognitive structure for the solution of (visual) comparison tasks – *assessment–memorisation–comparison* – the main hypotheses were formulated.

In order to test these hypotheses and construct a comprehensive "image" of line segment assessment and comparison from the various cognitive processing steps, the procedural concept must be developed accordingly. The emerging general structure should reflect the processing steps so that, in the end, it is possible to describe the mechanisms involved in line segment perception. The empirical findings will then be formalised within a mathematical model. The following paragraphs sketch the sequence of experimental procedures that the investigation will follow.

Basically, three psychophysical methods are most common in experiments concerned with the assessment of object proportions: The method of adjustment, the method of constant stimuli and the method of limits (see Section 2.2). For the present investigation of a visual comparison paradigm the first two methods appear best suited and will be used as follows:

Method of adjustment: Consider an experimental setting with a stimulus presentation analogous to the one that can be seen in Figure 3.6. Here, two line segments are simultaneously presented side by side. If the subject's task is to adjust one of the

Figure 3.6: Which of the two line segments is longer?

line segments' length (*comparison* stimulus) in order to match the length of the corresponding segment (*target* stimulus), the following processing steps must be performed for task completion:

(a) Visual exploration and memorisation of the target stimulus.
(b) Shift of attention to the comparison stimulus.
(c) Visual exploration of comparison and matching with memorised length information of target.
(d) Adjustment of comparison according to memorised length – if necessary.
(e) Shift of attention to target.
(f) Validation of adjustment.
(g) Re-iteration of the previous steps in case validation fails or is unsatisfactory.

These items represent the various steps that determine line segment length comparison. They present an "extension" to the cognitive structure and also describe the assessment–memorisation–comparison steps in greater detail – given such a task. However, it is already clear that such a complex setting and the possibly interacting processes could turn out to be too difficult to understand all at once. Thus, it may be a good approach to first choose a simpler setting in order to observe isolated phenomena which may then be easier to explain. Using the method of constant stimuli it should be possible to eliminate at least one factor – namely the influence of *length adjustment* – to achieve this goal. Length adjustment must be considered a *dynamic* process as the stimulus changes its length (its end points "move") during the adjustment step(s).

Method of constant stimuli: Rather than dynamically adjusting the line segment length to match the target and comparison stimuli, the method of constant stimuli that we favour for this investigation requires subjects to make a *simple binary decision* – for example, which of the two stimuli is the longer one. The sequence of processing steps for task completion is similar to the previous one, but does not include the step of adjustment of line segment length.

When dynamic stimuli are used, it is usually difficult to attribute particular shifts of attention uniquely to either these adaptation processes – as dynamic processes, i.e. movement or stimulus changes, are well known to be prime attractors for visual attention – or to an influence of specific stimulus attributes. The elimination of the dynamic process of line segment length adjustment should facilitate the monitoring and understanding of comparison processes and the influence of line segments attributes thereupon. This *static* procedure should be particularly beneficial for the interpretation of eye-movement patterns and associated attention processes.

If considered in detail, the proposed discrimination task implicitly suggests a variation of *discrimination difficulty*. Here, it appears to be particularly sensible to distinguish between an *"easy"* and a *"difficult" discrimination task condition*, as these might lead to rather interesting and very different processing strategies. As outlined in Section 2.4, an easy discrimination task could be solved *"holistically"* without much focused information acquisition whereas the difficult condition might require an *"analytic"* processing mode.

But, what could be appropriate definitions for the easy and difficult conditions? In fact, the experiment described above, which applies the method of adjustment, should help to solve this problem. The results obtained here yield information on how accurately subjects can match the length of two line segments. We can then use this data to infer which differences between line segment lengths are difficult to distinguish – obviously those that lie within this accuracy – and which are easy to distinguish – those that lie considerably outside the accuracy. This distinction thus determines the easy and difficult conditions for an experiment using the method of constant stimuli.

An aspect not explicitly accounted for in the sequence of processing steps so far, but one that was hypothesised to greatly affect the visual exploration, inter-stimulus comparison and attention processes, is the contribution of *peripheral vision*, viewed in the context of *stimulus decomposition and fusion*. As formulated in the hypotheses (see Section 2.4), it should initially be considered in isolation and, in a next step, must be integrated in the final explanatory model. The next paragraphs address procedural considerations associated with experiments investigating peripheral vision in general and propose specific experimental procedures for the line segment assessment and comparison paradigm.

The investigation of peripheral vision always presents a challenge to experimenters and requires a particularly sophisticated experimental design: It must be ensured that subjects do not foveally look at the stimulus relevant to the investigation, but that the stimulus is visible for the subject in a specific *eccentricity region* instead. Maintaining such a "seeing without looking" condition is usually not too difficult for short presentation times, for example when tachistoscopic displays are used . Here, cues are presented and foveally viewed by subjects prior to the stimulus in question which subsequently appears in the designated periphery of the visual field for a very short time only. However, with prolonged stimulus presentation times, it is found to be increasingly difficult to prevent subjects from foveally looking at the stimulus. Even with sophisticated pre-cuing and distractor tasks, it cannot always be ensured that subjects look where they are supposed to for the duration of the experiment. Furthermore, it is difficult to reliably state if subjects obey to the rules of "not looking". Finally, it is at least controversial if the distractor tasks do not influence the performance of peripheral perception and consequently bias the experimental findings.

Rather than indirectly generating peripheral viewing conditions accompanied by the above-mentioned uncertainties regarding validity, an alternative approach seems feasible: The monitoring of eye movements to ensure that peripherally presented stimuli are indeed viewed peripherally. Specifically, two options are available with such a method:

(a) *Offline:* Eye movements are monitored "in the background", i.e. they are recorded during the experiment and analysed offline *after* task completion to select "valid" (see below) trials.

(b) *Online:* The EyeLink eye tracker makes online tracking of eye movements feasible. As already described in Section 1.4 and, in more detail, in Section 3.1, this feature allows for the almost instantaneous analysis of the eye-gaze data just measured *during* the experiment.

In both cases, trials are rendered valid if, for the entire display time, subjects view the stimulus peripherally only and make no fixations outside a small, pre-defined region around a designated fixation point. The "active" monitoring of eye movements online, however, has clear advantages over the "passive" offline method: Online eye-movement monitoring may provide feedback as to whether a trial was valid or not *during* the experiment. In contrast, feedback is only available *after* the experiment when eye movements are monitored offline. Online feedback must certainly be preferred as it usually encourages subjects to produce more valid trials. This generates more valid data per subject for analysis. Furthermore, the procedure can be interrupted as soon as fixations are made outside a pre-defined region. In addition, invalid trials can be repeated to obtain an equal number of valid trials from all subjects in order to minimise bias induced by individual subjects.

Taking these preliminary considerations into account, it is evident that the choice of an *active, online eye-movement monitoring method* is most favourable for validity tests in experiments that investigate *peripheral vision*. For the research projected here it appears to be most promising to investigate the assessment of *lengths* and *orientations* of line segments presented in different *eccentricity regions*. We expect eccentricity to have a considerable influence on the processes involved in the perception and assessment of a line segment itself as well as on the processes that guide comparison in the above-mentioned line segment adjustment and discrimination tasks.

For the investigation of eccentricity effects, we shall use a variant of the method of adjustment. Rather than simultaneous comparison, we will use *sequential* comparison so that (roughly) the following sequence of procedural steps emerges:

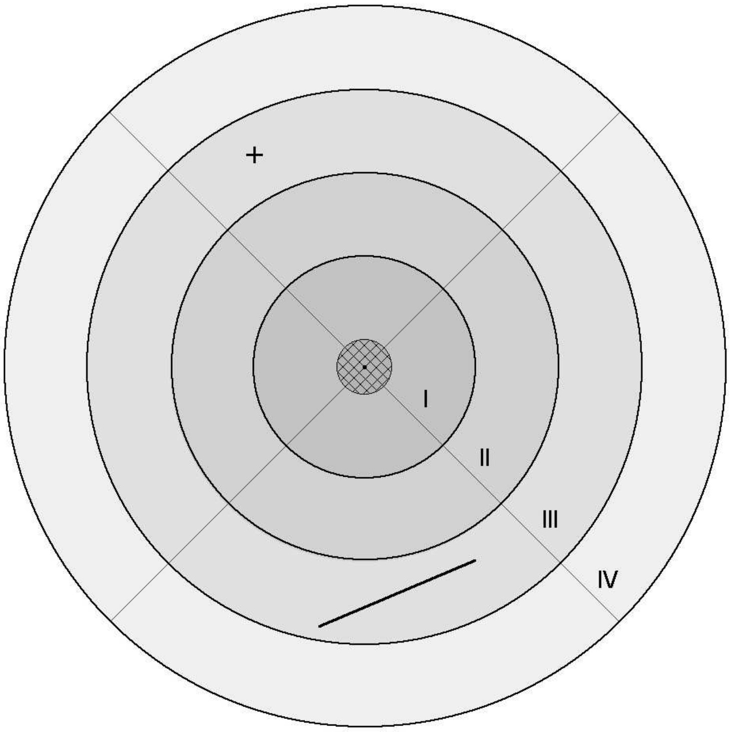


Figure 3.7: Experimental setting for the investigation of eccentricity effects on position and line segment perception. The central dot serves as a fixation marker the subjects have to observe while trying to assess either length or orientation of the peripherally presented line segment or the position of the peripherally presented cross. The possible eccentricity regions I–IV are marked and shaded in the figure for clarity reasons only.

(a) Presentation of a line segment (target stimulus) at an eccentric position relative to a central fixation marker (see Figure 3.7) – restricted, gaze contingent viewing condition.

(b) Blanking of the display.

(c) Presentation of a line segment (comparison stimulus).

(d) Adjustment of comparison length or orientation, respectively, to match corresponding dimension of previously viewed target – unrestricted free gaze condition.

With respect to the effects of eccentricity on line segment perception relevant here, sequential comparison is, in fact, the best option for obtaining the desired data. By presenting only one stimulus at a time, subjects have a single task to accomplish with every procedural step. This is in particular important during the gaze contingent viewing of the target where interference from concurrent stimuli or parallel tasks is not intended (see above). Rather than trying to assess the designated dimension of a peripherally visible target and simultaneously adjust the comparison line, subjects "only" have to accomplish the assessment part – which alone is difficult enough. No task interference from the simultaneous adjustment will bias or even dominate the perception processes. On the other hand, it can be argued that the time between the end of the presentation of the target and beginning of the presentation of the comparison has a negative effect on reproduction accuracy ("memory effect"). However, we argue that this possible objection is more than compensated for by the procedural advantages in the previously accounted respects.

As line segment length assessment can be thought of as a process that involves *stimulus decomposition* and the calculation of the distance between the line segment's two *end points* (*data fusion*) these end points evidently play an important role. Particularly important for accurate length assessments would thus be the accurate assessment of end point positions. In analogy, the same is true for line segment orientation assessment when this is viewed as a process that is guided by the calculation of the relative positions of the two end points to each other. As a consequence, it appears sensible to conduct a further experiment in order to explore how accurately *position* (or *location*) can be assessed.

For such an experiment, the design of the previous setting would have to be altered only in one minor point: A position marker rather than a line segment is displayed within a certain eccentricity region of the fixation point (see Figure 3.7). Furthermore, the adjustment procedure (see item (d) above in the sequence of procedural steps) now requires the positional reproduction of the target marker.

As the performance in position estimation, i.e. the levels of accuracy achieved, might vary with the *position of the target relative to the fixation point ("meridial position")*, either horizontal or vertical, an investigation of this factor is also advisable (cf. Gregory, 1970; Schneider, 1978; Prinzmetal & Gettleman, 1993; Armstrong & Marks, 1997). The thin diagonal lines in Figure 3.7 indicate these distinct areas. As results from position assessment might serve as the basis to understand more about the processes involved in line segment length and orientation assessment – not only in peripheral vision – this (position assessment) experiment should be conducted first.

Thus, in order to obtain valuable data for analysis that yield useful results regarding the visual perception of line segments and the assessment of selected attributes, the following sequence of experiments is proposed:

(1) Sequential comparison –
Eccentricity effects in position and line segment perception

- Experiment E0: The basis – Position assessment
- Experiment E1: Length assessment
- Experiment E2: Orientation assessment

(2) Simultaneous comparison –
Similarity effects in line segment perception

- Experiment S1: The basis – Dynamic adjustment in length matching
- Experiment S2: Holistic vs. analytic processing – Binary judgements in length discrimination

So far, we have established the methodological preliminaries for the upcoming experiments with respect to technological aspects, stimuli and procedural strategy. In the course of this, we incidentally introduced the relevant factors the investigation will focus on and their effects on specific variables as well. The next section will now more formally define and specify these parameters, i.e. *independent* and *dependent variables*.

3.4 Independent and Dependent Variables

Independent and dependent variables are crucial for a quantitative analysis of the data recorded during experiments. These variables must be chosen sensibly in order to obtain valuable conclusions regarding the quantitative relations between stimulus conditions on one side and experimental observations on the other. In the present investigation, the stimuli, i.e. line segments, are conveniently determined by several quantitative parameters. A *statistical* analysis of these stimulus parameters, such as line segment length or orientation, with regard to their effects on eye-movement and "conventional" psychophysical parameters should yield the desired quantitative results. Which exactly will be the independent variables – or *factors* – here and how will we define the dependent variables – or *variates* –, in particular for the analysis of eye-movement parameters?

3.4.1 Independent Variables

In Section 3.2.2 we already introduced most of the independent variables as the attributes that determine line segments. These should thus be systematically varied in the experiments. In addition, the list of quantitative parameters to be varied was not yet complete. Let us now briefly consider the definitions of Section 3.2.2 and add the still missing factors.

The following parameters that characterise the stimuli line segments are defined already as possible independent variables:

- Line segment length.
- Line segment orientation.
- Line segment colour/contrast.
- Line segment breadth/width.
- Line segment continuity.

From these factors, *length* and *orientation* are apparently the most characteristic attributes of line segments (see definition for "line segment", Section 3.2.2). As these two variables in particular affect the extent of the stimulus, they are most important for the investigation of line segment length assessment with respect to their influence on eye-movement parameters. We thus propose to examine the "main" independent variables length and orientation within experiments. This restriction is further advisable as the combination of variations of all factors within an experiment would lead to too large a number of experimental trials. Subjects would need too much time to complete the experiment which might lead to fatigue effects and could bias the results. Furthermore, the need for repetition of conditions within subjects could not be met. This then would affect statistical validity of the quantitative analysis. Finally, we must not forget that there is one extra independent variable for each of the two proposed series of experiments which must be included in the analyses as well:

- Sequential comparison experiments: *Eccentricity of the stimulus presentation.*
- Simultaneous comparison experiments: *Difficulty of discrimination.*

The additional (obvious) factor *eccentricity* (of presentation) was introduced briefly already for the experiments concerned with eccentricity effects in position and line segment perception. The systematic variation of the eccentricity levels so that they coincide with conditions of foveal, parafoveal and peripheral viewing will be explored in Experiment E0 with respect to position assessment accuracy. In fact, a distinction will be made here between the presentation of the position marker along the horizontal or vertical meridians relative to the fixation point. This *horizontal/vertical* (or *meridial position*) condition represents a further independent variable.

For the experiments concerned with similarity effects in line segment perception, the factor *difficulty* (of discrimination) should additionally be varied to explore different visual processing strategies (Experiment S2). The possible discrimination levels "easy" and "difficult" will be investigated with respect to "holistic" or "analytic" processing patterns, manifested in distinct differences in eye-movement parameters. The levels of this factor are determined by the previously conducted Experiment S1 that assesses line segment length matching accuracy.

3.4.2 Dependent Variables

The relevant independent variables which determine the stimuli and details of their presentation were listed in the previous paragraphs. Due to the varying experimental goals, these factors are not all the same across experiments. In analogy, the relevant dependent variables will differ from experiment to experiment as well. Which are the dependent variables that yield the most interesting information on line segment assessment in each experiment?

The first series of Experiments E0–E2 makes use of the eye tracker only as a control device for eye movements. The eye tracker monitors whether a fixation restriction imposed on subjects is met. As eye movements are thus suppressed, no sensible eye-movement data are available for analysis. Instead, the following dependent variables are measured (for an illustration of selected measures see Figure 3.8):

Reaction time (RT): RT denotes the time from the onset of the stimulus displayed in an eccentricity region to the subject's manual response which ends the "fixed focus", peripheral viewing condition. RT is measured in milliseconds (ms).

Radial deviation (DX): After subjects peripherally view the target marker and the display is blanked, they position a comparison marker at the location where they

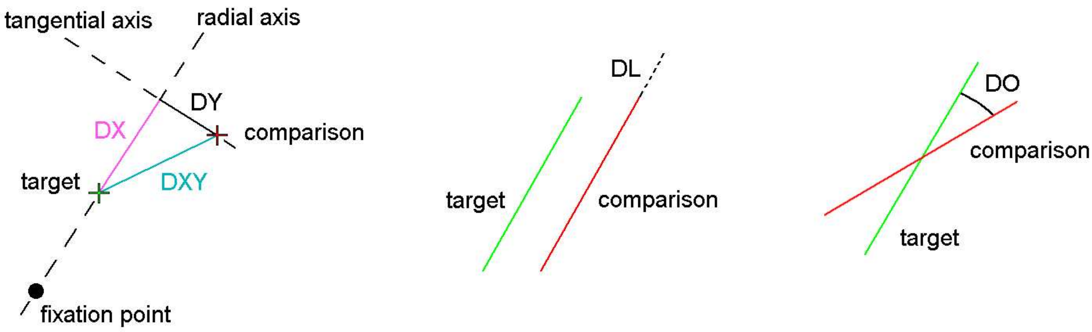


Figure 3.8: Left: Positional deviations in Experiment E0. Middle: Length difference in Experiment E1. Right: Orientation difference in Experiment E2.

perceive the target. Eye movements are not restricted then. DX is the positional deviation (mislocation) of the comparison marker in relation to the original position of the target marker along the *radial* axis. The fixation point at the center of the display marks the origin of the radial axis. Rather than measuring the deviations within a coordinate system oriented along the horizontal and vertical display dimensions, we favour measurement within a coordinate system formed by the radial axis and the associated perpendicular (*tangential*, see below) axis. Thus, the new coordinate system is Euclidean, rotated around its origin (subjects' fixation point). Due to a radial-symmetric arrangement of eccentricity regions around the fixation point, such a coordinate system is advisable here in order to obtain valid data regarding eccentricity effects. DX is measured in degrees (^{o}) of visual angle (Experiment E0).

Tangential deviation (DY): This is the positional deviation of the comparison marker in relation to the original position of the target marker perpendicular to the radial axis. DY is measured in degrees of visual angle (Experiment E0).

Euclidean deviation (DXY): This is the Euclidean distance between the positions of the comparison and the target markers. DXY is measured in degrees of visual angle (Experiment E0).

Length difference (DL): DL is the difference between the length of the comparison line segments and the original length of the target line segment. DL is measured in degrees of visual angle (Experiment E1).

Orientation difference (DO): DO is the difference between the orientation of the comparison line segment and the original orientation of the target line segment. DO is measured in degrees (^{o}) (Experiment E2).

In the second series of experiments, eye movements are recorded and analysed – along with the "conventional" psychophysical data – in both the stimulus matching (Experiment S1) and the discrimination (Experiment S2) tasks. The following dependent variables are measured (Figure 3.9 intuitively illustrates the relevance of (most of) the measured dependent variables):

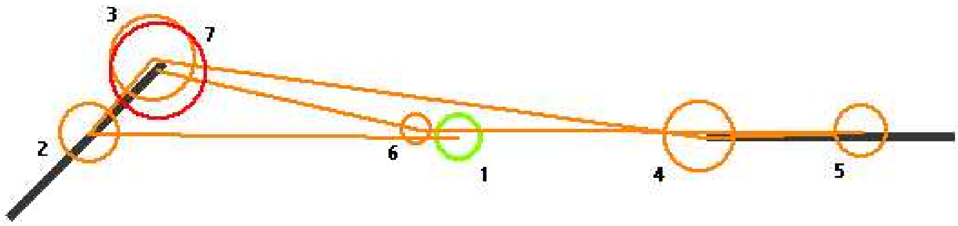


Figure 3.9: A typical gaze trajectory recorded in Experiment S2. Fixations are denoted by circles whose diameters reflect fixation duration. The straight lines represent the saccades that link successive fixations. The fixations are numbered so that their temporal occurrence becomes clear. The green circle marks the first, the red circle the last fixations in this trial.

Reaction time (RT): RT denotes the time subjects take to either match the comparison line segment length to that of the target (Experiment S1) or to decide which of the target or comparison line segment is the longer one (Experiment S2). RT is measured in milliseconds (ms).

Length difference (DL): See definition of DL for Experiment E1. DL is an important dependent variable in Experiment S1 as it greatly determines the computation of line segment lengths that constitute the "easy" and "difficult" conditions in Experiment S2.

Correctness of discrimination (DC): This dependent variable will be measured in Experiment S2 to determine the percentage/ratio of correct responses regarding the subjects' decision as to which of the two stimuli is the longer one. DC serves as a control to check whether the "easy" and "difficult" discrimination conditions were adequately established in the previous Experiment S1.

Number of fixations (NF): This is the total number of fixations per trial, accounting for fixations on both the target and comparison stimulus. In order to investigate the influence of the dynamic adjustment task in Experiment S1, NF will be analysed separately for the two hemifields where target and comparison are shown.

Fixation duration (FD): FD denotes the time that every single fixation lasts and is measured in milliseconds (ms). Due to the EyeLink eye tracker's temporal resolution of 250 Hz, fixation duration is accurate within a range of 4 ms.

Number of saccades between hemifields (SB): SB is the number of saccades that are made across the display from target to comparison or vice versa, i.e. the number of inter-stimulus saccades.

Number of successive fixations within the same hemifield (FW): This is the number of successive fixations that occur within one hemifield before the eye gaze is directed to the other hemifield. This measurement is of particular value when we consider only those fixations in a hemifield that lie within the immediate region covered by the stimulus.

Saccade length (SL): Saccade length is defined as the spatial distance between two successive fixations *within* the region of either the target or the comparison. As saccades between the two hemifields are presumed to be invariant in length, inter-hemifield saccades are excluded from the analysis of saccade length. SL is measured in degrees (^{o}) of visual angle.

3.5 Summary

The motivation to study line segment assessment with particular emphasis on eye movements and visual attention, as discussed in Chapter 2, and the definition of the methodological preliminaries in this chapter have cleared the ground for our investigations.

The review of previous research, sometimes with (Section 2.3), but often without the integration of data from eye tracking experiments (Section 2.2), rendered it rather promising to pursue an eye-movement approach to learn more about the principles underlying the visual perception of object proportions. We consider line segments to be ideal targets for empirical investigation as they are both basic and highly versatile. Despite their apparent simplicity their appearance can vary greatly. In addition, the line segments' attributes that determine their appearance can be conveniently formalised in a set of quantitative parameters which is ideal for statistical analysis. As there is strong indication that attention processes play an important role in the perception and assessment of line segments, we should be able to define the relation between the quantitative parameters that determine line segments and the observations made in eye-movement experiments, i.e. quantitative data regarding eye-movement parameters.

From the technological point of view (Sections 1.4 and 3.1), ideal conditions are provided by using the EyeLink eye tracker for recording eye movements during experiments. The EyeLink system offers the flexibility required for a controlled presentation of computer generated stimuli with the desired stimulus parameters. Stimulus presentation, recording of eye movements and subjects' manual response are synchronised and guarantee high temporal and spatial accuracy of the experimental data. Eye-tracking experiments using the EyeLink system provide experimental data which is easy to access and process. Furthermore, the eye-tracker headset is comfortable to wear so that no negative influence from the technical equipment on the experimental performance of subjects is to be expected. In the present investigation, the fact that eye-movement data is available online is a great advantage for the experimental procedure of Experiments E0-E2. Rather than controlling subjects' gaze by procedures that might interfere with the intended processes of peripheral vision, the eye tracker monitors the subjects' gaze and intervenes in case a position different from the one requested is fixated.

With the more detailed specification of experiments (Sections 3.2–3.4), i.e. the stimuli, the experimental procedures, the overall procedural strategy and the definition of independent and dependent variables, a clearer image was generated of what will be investigated and how results will be obtained in order to test the hypotheses formulated in Section 2.4. Two series of experiments will be conducted to investigate the assessment of line segments. The first series closely examines the effects of eccentricity on position and on line segment assessment. Furthermore, the effects of the factor meridial position are investigated, assuming that assessment accuracy is better for stimuli presented along the horizontal than along the vertical meridian. (N.B.: As we will later learn, this factor must only be considered for position assessment.) In particular the eccentricity effects are thought to be relevant in simultaneous line segment assessment as well: Both saccade planning and the processing of relevant stimulus attributes are assumed to be influenced by peripheral perception and may require *stimulus decomposition*. The findings of the eccentricity Experiments E0–E2 may thus help to account for or explain the observed behaviour in Experiments S1 and S2. The effects of the *difficulty of a discrimination task* on line segment length assessment are explored in Experiments S1 and S2. Depending on the *similarity* of two line segments, we expect to obtain evidence for two distinct processing strategies, either *"holistic"* or *"analytic"*. In particular in analytic mode line segments could be *decomposed* for length assessment: End point are inspected to acquire location data. This data is then *fused* to obtain the distance between the end points which thus yields the line segment length. Decomposition and fusion might be accomplished either *peripherally* or require *saccadic visual measurement*. These strategies should involve different patterns of distribution of attention and therefore result in significant statistical differences when comparing the relevant *eye-movement parameters* (and psychophysical data as well). Correspondingly, the processing strategies should also yield two distinct, characteristic *gaze trajectories*.

With all preliminaries discussed, the empirical research can begin. The first experiments that investigate the eccentricity effects on positional and line segment length and orientation assessment accuracy in a sequential comparison setting will be described in the following chapters.

Chapter 4

Sequential Comparison – Eccentricity Effects in Position and Line Segment Perception

After we established the preliminaries for the present research in the previous chapter(s), the more or less coarse "plans" laid out there have to be finalised and put into practice, i.e. we have to precisely specify the experimental methods and conduct the actual experiments.

As an overall goal, we are primarily interested in the processes that characterise the visual perception and the assessment of line segments and, in particular, how visual attention guides comparison processes of line segment length. However, we are well aware of the fact that we probably cannot understand all at once how humans accomplish this rather complex perceptual and cognitive task. Instead, we think it is worthwhile to identify and explore the fundamental mechanisms behind it and find out how they interact. An investigation of these less complex mechanisms in isolation should yield results that contribute to our understanding of the complex task of line segment assessment. If we then manage to integrate the results appropriately, their "sum" might lead to the desired understanding of the whole process. We thereby propose a *bottom-up* "explorative" strategy.

We already identified the influence of peripheral vision in Section 3.3.1 as one of the fundamental factors in the assessment of line segments. This conclusion is based on observations from various authors as presented in Sections 2.2 and 2.3. In summary, their findings suggest that information from the *peripheral visual field* yields necessary or even essential data for *object identification* and the processing of *object attributes*. It was also hypothesised that complex stimuli are *decomposed*. Less complex attributes are assessed separately and then combined (or *fused*) to yield the stimulus attribute whose assessment was originally intended.

However, data is often perceived in a distorted manner which then leads to the misjudgement of the original dimensions. This is in particular true for line segments. Due to their extension in only one dimension they are usually not very "compact" – unless they are very short – so that peripheral visual processing is essential, for example, to determine line segment length.

Peripheral processing should play an even more important role in line segment comparison tasks. Here, not only the length of each segment must be assessed, but the comparison has to be accomplished. This might often be greatly facilitated by peripherally assessing the relevant attributes of *both* the target and comparison line segments at the same time – *memory* involvement as required in sequential comparison could thus be minimised. We will address this simultaneous comparison in the second part of our investigations and focus on a "forced" sequential comparison with only one stimulus visible at a time in these earlier chapters.

Although a number of experiments were conducted with a view to eccentricity effects on line segment assessment, data cannot simply be taken over or adopted for our investigation. Depending on the stimuli, the specific task and the goal of the investigation, rather inconsistent results emerged and sparked dispute over the validity of possible interpretations (see, for example, the controversy between Engen, 1971, Bogartz, 1979 and Fagot, 1982). Even almost identical experiments sometimes produced contradictory or inverse findings. Stevens (1908) and Helmholtz' (1910/1962) inconsistent results regarding the apparent sizes of peripheral objects may serve as an early prototypical example.

Apart from these factors, the experimental procedure in general and the procedure to maintain constant peripheral viewing conditions throughout the experiment in particular were not always optimal in the past. As discussed in detail in Section 3.3.1, distractor tasks to control the eye gaze position are at least controversial. They might induce unintended side effects that could also be difficult to identify. Thanks to now-available *online* eye tracking available now, these problems can be eliminated and undistracted, "pure" peripheral viewing conditions can be reliably generated and maintained.

However, as further explained in Section 3.3.1 we will not begin with an experiment that assesses line segment length or orientation. Instead, we use an even more simplified scenario to serve as the basis for the investigation where the positional assessment in specific eccentricity regions is explored.

Subjects' comparison acuity deteriorated drastically in experiments that only displayed line segment fragments or obliterated the terminal sections so that the whole line segment was not visible at any one time (see Section 2.3, e.g. Buchsbaum, 1972; Ikeda et al., 1977). These findings lend support to our assumption that end point information is vital for the assessment of line segment attributes such as length and orientation (*decomposition hypothesis*). Furthermore, this could lead to the conclusion that the accuracy in line segment assessment is closely related to the accuracy in positional assessment. It might thus be possible to directly infer line segment length or orientation accuracy from position assessment accuracy: When people assess the positions of two markers in an eccentricity region and subsequently compute the difference, i.e. distance, between the two position assessments (including their positional "uncertainties"), this might yield a similar result to assessing the length of a line segment in the same eccentricity region and determined by end points that coincide with the two previously shown markers.

In order to test these assumptions – and hopefully find support for them – we will conduct

- Experiment E0 – Position assessment
- Experiment E1 – Length assessment
- Experiment E2 – Orientation assessment

in this order. Subsequently, we will develop a model that takes into account the findings from Experiment E0 and will ideally be able to replicate the empirical results from the Experiments E1 and E2 in a way as hypothesised in the last paragraph (see above).

4.1 Variables and Stimuli

This section describes the algorithmic generation of the stimuli for all three Experiments E0, E1 and E2 and motivates the choice of levels for the independent variables in

- Experiment E0:
  - Eccentricity
  - Meridial position relative to the central fixation point
- Experiments E1 and E2:
  - Eccentricity
  - Length
  - Orientation

Before we can determine the algorithm for the generation of stimuli, we have to decide which would be sensible choices for the different levels of the independent variables. Let us first consider the independent variable which will be studied in all three experiments, namely *eccentricity*.

4.1.1 Levels of Independent Variables

If the same independent variable is being used in different experiments, it is advisable as a general rule to define the same levels for that independent variable in each experiment. If either the number of levels or their magnitude are not maintained across experiments, this could render a comparison between experiments rather difficult and give reason for controversy – if not make such an analysis impossible. Both the number of levels and their magnitudes should consequently be agreed on only when it is clear that their choices are compatible with further independent variables that determine the stimuli appearance in all experiments concerned. Of course, this applies to the factor eccentricity in our investigation as well. As we intend to draw conclusions from findings of one experiment in order to help explaining the results of the others, the levels and their magnitudes of the independent variable eccentricity should be kept constant across Experiments E0, E1 and E2. Which values make sense for the definition of the eccentricity regions?

In a first rough approximation, we will distinguish between three different regions of eccentricity so that stimuli can be viewed either *foveally, parafoveally* or *peripherally*. Several studies (e.g. Tsal, 1983; Wright & Ward, 1994; for an overview see Posner, 1980, and Matlin & Foley, 1997) attempted to quantify these categorisations, i.e. assign each of these regions a value in terms of visual angle they subtend. In accordance with the decrease of retinal receptor density from the fovea to the periphery and the accordingly decreasing representation accuracy in the visual cortex, literature (see above) suggests that the foveal region covers eccentricities of up to 3^o and the parafoveal region eccentricities of up to 10^o. Visual information that is present in excess of 10^o from the fixation point is supposed to be processed peripherally[1]. These boundaries are not distinct and sharp, but rather continuous and smooth. (N.B.: Terms such as "peripheral viewing" or "peripheral perception" are commonly used to denote *extra-foveal* processes, i.e. processes that occur in either parafoveal or peripheral regions. This well-established terminology has also been used in this thesis although it might appear slightly ambiguous with respect to the definition of the "peripheral" eccentricity region.)

In order to give the reader a realistic impression of the actual dimensions of the eccentricity regions, attention is drawn to Figure 4.1. If the viewing distance measures approximately 40 cm and the black dot on the far left is fixated, the images of the red triangle, the blue square and the green circle are located in the foveal, the parafoveal and the peripheral region, respectively. The reader will notice that it becomes increasingly difficult to identify the objects' main attributes of colour and shape the further the stimulus is moved out towards the periphery. It should further be noted that colour is apparently easier to identify than shape, in particular in the far periphery.

The "classical" categorisation of the eccentricity regions into foveal, parafoveal and peripheral implies the choice of three levels for the independent variable eccentricity. However, in order to achieve a finer granularity of observations, a distinction has been made between *four* eccentricity levels I-IV: The (region of) Eccentricity I should allow for foveal processing of the stimuli presented within that range. The parafoveal region is split up into the eccentricity regions II and III. This is motivated by the fact that 3^o–10^o covers a rather large region of the visual field. We expect to find significant processing differences within the parafoveal region, depending on near-foveal and near-peripheral stimulus presentation. The choice of Eccentricities II and III should account for this distinction accordingly. Due to the restricted display space available on the computer screen, the peripheral presentation region Eccentricity IV must be limited to 13^o. The procedure (see below) requires subjects to observe a fixation point located at the center

[1] It could, however, be argued whether the ranges should indeed be set in analogy to the distribution of retinal receptors and thus be equal for all types of stimuli and stimulus dimension to be judged. Alternatively, it would be possible to define eccentricity regions according to the perception acuity of the respective dimension. Support for such a distinction is not very widespread as it leads to different definitions of eccentricity regions for different stimuli which complicates inter-stimulus comparison. We share this view and think that the above-mentioned ranges of eccentricities represent the most appropriate guidelines for a categorisation.

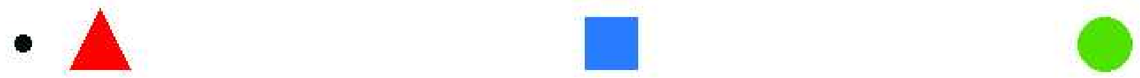


Figure 4.1: Illustration of eccentricity regions: If viewed from a distance of approximately 40 cm with the black dot fixated on the far left, the image of the red triangle is located in the foveal, the blue square in the parafoveal and the green circle in the peripheral region.

of the display. With a viewing distance of approximately 60 cm from a computer screen with a 20-inch screen diagonal, stimuli cannot be presented in eccentricities greater than 13^o in each direction of the fixation point. The stimuli will accordingly be displayed within four eccentricity regions which cover the following ranges (in degrees of visual angle):

- Eccentricity I: 1^o–4^o
- Eccentricity II: 4^o–7^o
- Eccentricity III: 7^o–10^o
- Eccentricity IV: 10^o–13^o

In fact, the choice of the ranges of the eccentricity levels is closely related to the choice of levels for the independent variables line segment *length* and *orientation* in Experiments E1 and E2, respectively. Let us consider the line segment length factor first.

An intuitive classification of line segment lengths would suggest line segments that are "short", "intermediate" and "long". But how can we quantify this? The approach we take is guided by factors that have to be taken into account when designing the stimuli for the later simultaneous line segment length comparison experiments. With respect to the goals of Experiments S1 and S2, it appears to be appropriate to choose line segments whose lengths can either be perceived foveally or require parafoveal or peripheral processing. In a comparison scenario with unrestricted eye gaze, shifts of visual attention are then likely to be performed for "longer" line segments in order to foveally acquire relevant dimension information. We expect that this is true in difficult discrimination tasks in particular. Such a visual strategy would support an analytical processing hypothesis, in contrast to possibly preferable holistic processing in "short" line comparisons, in particular for easy discrimination tasks. As these considerations are also of some relevance in Experiments E1 and E2 and, furthermore, as conclusions from these experiments might contribute to the explanation of some aspects of the observations in Experiments S1 and S2, the selection of levels as discussed above is the most preferable.

However, we have to take into consideration that, due to the size of eccentricity regions, the line segment lengths are limited and cannot be chosen in analogy to the ranges of the eccentricity regions. Its eccentricity regions are radial-symmetric in shape, the maximum line segment length is determined by the size of the innermost eccentricity region, i.e. Eccentricity I. A line segment that yields the maximum possible length and can still be displayed in full within that eccentricity region must be oriented tangential to the boundary of the radial-symmetric area around the fixation point. If we introduce a further constraint, namely that the line segments must not be displayed within a certain margin m of the eccentricity boundaries, the maximum line segment length l_{max} is computed as

$$l_{max} = 2 \cdot \sqrt{(r_2 - m)^2 - (r_1 + m)^2} \quad (4.1)$$

where r_1 denotes the radius of the fixation region boundary – which equals the inner boundary of Eccentricity I, i.e. 1^o – and r_2 denotes the radius of the outer boundary of Eccentricity I, i.e. 4^o. Figure 4.2 illustrates the constraints that determine the computation of the maximum line segment length l_{max}.

When we set the disallowed margin m to 0.3^o, only line segments with a length of up to 7^o can be placed within the Eccentricity I without overlap of the neighbouring eccentricities (see Figure 4.5). We thus select the following lengths for line segments as displayed in the Experiments E1 and E2 (in degrees of visual angle):

- Short: $1^o \pm 0.3^o$
- Intermediate: $4^o \pm 0.3^o$
- Long: $7^o \pm 0.3^o$

In order to keep differences equal between the levels of the independent variable line segment length, the short line segments were chosen to be 1^o and the intermediates to be 4^o. Although not exactly, these lengths still reflect the foveal, parafoveal and peripheral regions of the visual field in good approximation. In an attempt to minimise habitual effects that might occur when always exactly the same values have to be assessed, Gaussian "noise" is introduced that randomly varies the line segment length by 0.3^o around the short, intermediate and long levels listed above.

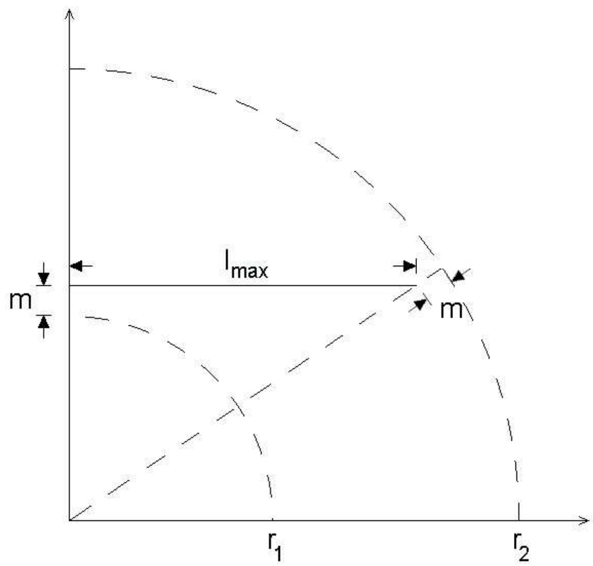


Figure 4.2: Restriction of line segment length in Experiments E1 and E2 due to eccentricity boundaries.

For another independent variable, orientation, the choice of levels and their magnitudes are restricted by the size of the eccentricity regions insofar as not all combinations of orientations and line segment lengths can be presented at all locations within the eccentricity regions. It is, for example, impossible to show a long, vertically oriented line segment at a position directly on or in proximity to the vertical meridian, i.e. above or below the fixation point. Such a configuration would result in the line segment's end partitions being visible in adjacent eccentricity regions rather than in the intended part of the visual field only. As we will learn in Section 5.2, results from Experiment E0 suggest that the meridial location of a stimulus, i.e. its position relative to the fixation point, does not affect the acuity of position assessment. If we assume that the same is true for length or orientation assessment, the meridial position will not have to be systematically varied as an independent variable in Experiments E1 and E2. Meridial position does therefore not constitute a critical factor and can be excluded from the list of constraints. This allows us to circumnavigate the problem of incompatible stimulus combinations with respect to orientation limitations.

For the independent variable orientation, the following levels are chosen:

- Horizontal: $0^o \pm 22.5^o$
- Oblique: $45^o \pm 22.5^o$ or $135^o \pm 22.5^o$
- Vertical: $90^o \pm 22.5^o$

To be precise, the orientation regions should indeed be called "near horizontal", "oblique" and "near vertical". The choice of the categories and their ranges appears appropriate as they cover all possible orientations. Rather than only investigating line segments that are oriented exactly horizontal, vertical or at an angle of 45^o, no habitual effects must be feared for orientation assessment due to the variation of line segment orientations around those angles. Figure 4.3 illustrates the ranges of possible angles for the three horizontal, oblique and vertical orientations. Each segment covers an angle of 45^o (22.5^o either side) around the respective guidance orientations of 0^o, 45^o and 90^o. The blue sample line segment shown in the figure is thus classified as belonging to the oblique range.

In order to test whether the meridial location of stimuli, i.e. their position relative to the fixation point, has an effect on position assessment, this additional factor is varied in Experiment E0. As earlier research suggested (e.g. Künnapas, 1955, 1957, 1959; Prinzmetal & Gettleman, 1993; Armstrong & Marks, 1997) acuity differences depending on whether stimuli were perceived either along the horizontal or the vertical meridian, these two (natural) categories are chosen for the independent variable meridial position in Experiment E0. The two diagonal light grey lines in Figure 3.7 or Figure 4.4 (top) define the segments. No further distinction will be made between either the left and right horizontal segments or the upper and lower vertical segments.

After the quantification of all relevant variables and the discussion in the previous paragraphs of constraints that an appropriate stimulus design has to comply with, these stimuli can now be generated algorithmically.

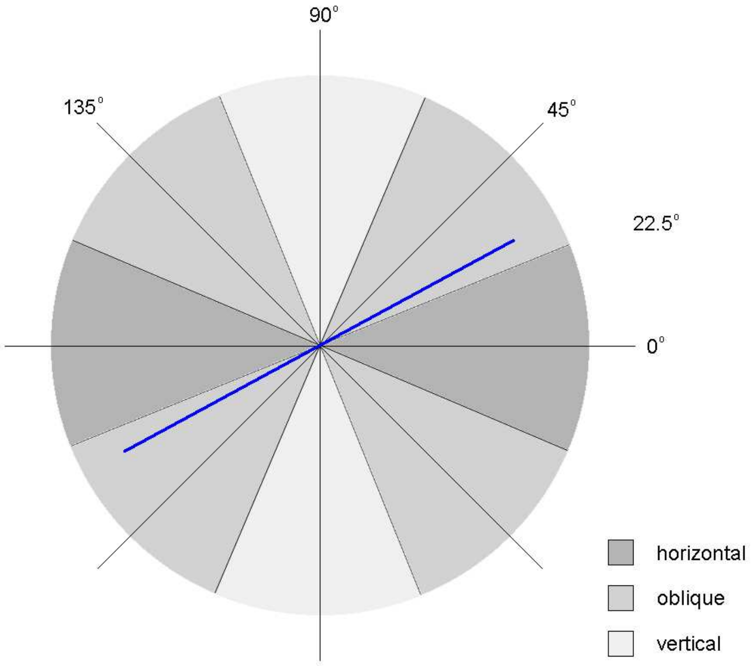


Figure 4.3: The ranges of the levels "horizontal", "oblique" and "vertical" of the factor orientation. The horizontal segments are coloured dark grey, the oblique segments medium grey and the vertical segments light grey. The blue sample line segment belongs to the oblique range.

4.1.2 Algorithmic Generation of Stimuli

Of course, instead of generating the stimuli that will be presented in the Experiments E0, E1 and E2 manually, i.e. composing the displays for each trial separately and "by hand" using a computer graphics program, we will automate this process. With the stimuli – position markers and line segments – whcih consist of very primitive graphical elements, the main goal of algorithmic stimuli generation in this instance is:

- Experiment E0: The computation of pseudo-random[2] marker positions so that an equal distribution of markers within the respective eccentricity regions and the meridial segments is achieved. All combinations of eccentricity regions and meridial segments should be equally accounted for by the generated marker positions.

- Experiments E1 and E2: The computation of line segments, i.e. the pseudo-random generation of their end points' coordinates, for all combinations of lengths, orientations and eccentricities of presentation. Again, the pseudo-random nature of the

[2]The term "pseudo-random" describes a randomisation process that is guided by constraints. Technically, this is usually achieved by restricting the random range so that it only reflects a certain condition. Example: Imagine you want to generate two random numbers from the range 1 to 20. If you introduce the constraint that one number has to lie between 1 and 10 and the other between 11 and 20, you cannot always be sure that random drawing of two numbers from the interval [1..20] meets this constraint. If you, however, pseudo-randomly draw one number from [1..10] and the second from [11..20], the constraint is always fulfilled. Pseudo-random procedures are very popular in psychological experiments where constraints ensure, for example, that an equal number of stimuli for all factor levels is generated – an essential prerequisite for a successful statistical analysis.

procedure automatically leads to an equal distribution of line segments within the respective regions. Furthermore, the algorithm has to make sure that the whole line segment lies entirely within its designated eccentricity region.

With the independent variables eccentricity (I–IV, i.e four levels) and meridial location (horizontal or vertical, i.e. two levels) set as discussed in the previous section, Figure 4.4 shows the algorithmically generated markers at their respective positions. Each subject will have to assess the position of a total of 360 markers, so that every combination of the two factor levels will be displayed $360/(4 \cdot 2) = 45$ times.

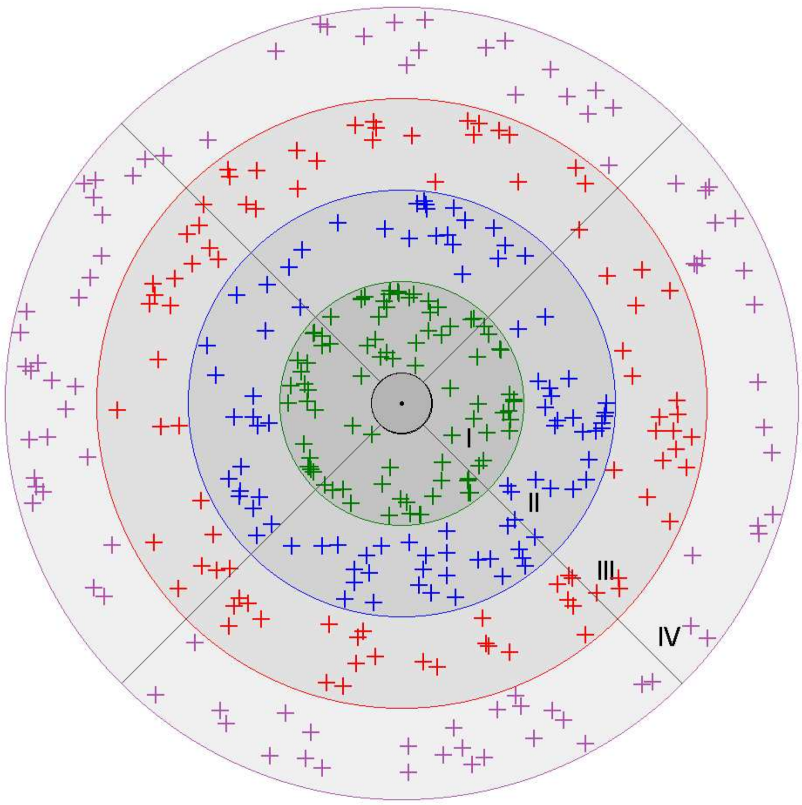


Figure 4.4: All position markers algorithmically generated for display in Experiment E0 (one marker shown per trial).

Due to the larger number of independent variable combinations in Experiments E1 and E2, we cannot have the subjects repeat the combinations quite as many times as in Experiment E0. With the independent variables eccentricity (four levels), line segment length and orientation (both three levels), $4 \cdot 3 \cdot 3 = 36$ individual cases have to be tested. As it turned out that subjects required a relatively long time of about 45 minutes to complete the 360 trials of Experiment E0, a repetition factor of 10 was introduced to obtain 360 trials per subject in Experiments E1 and E2 as well. This will still provide highly reliable data for a statistical analysis. The choice of a higher repetition factor and thus the increase of trial numbers and experiment duration does not appear feasible: Some subjects

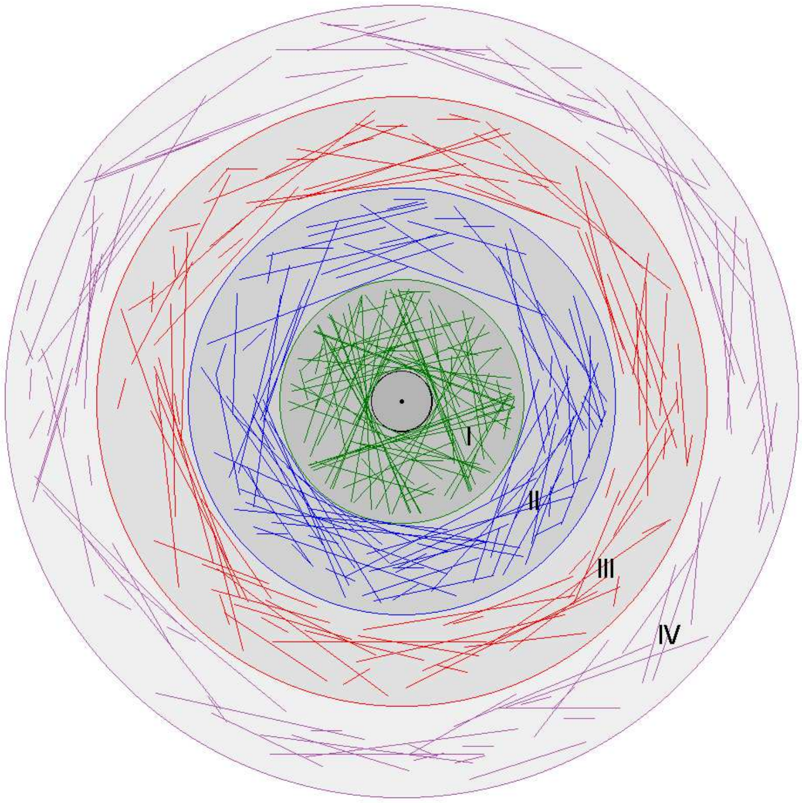


Figure 4.5: All line segments algorithmically generated for display in Experiments E1 and E2 (one line segment shown per trial)

complained of fatigue in Experiment E0, probably due to the tiring fixed-focus restriction. Figure 4.5 shows all line segments algorithmically generated for Experiments E1 and E2.

The following chapter will describe Experiment E0, the experiment that investigates the eccentricity effects on positional assessment accuracy in a sequential comparison setting. After explaining the particularities of the method for this experiment the results will be presented and discussed in detail.

Chapter 5

Experiment E0: Location Assessment in Peripheral Vision

Experiment E0 is the first in a series of three experiments that aim to establish and quantify the effects of eccentric stimulus presentation on the perception and assessment of specific stimulus dimensions. For the investigation, we explore the paradigm of sequential comparison, paired with the psychophysical method of adjustment. In order to control a restriction that is imposed on the subjects and requires them to only look at a designated region during target stimulus presentation, we monitor the subjects' eye gaze using the EyeLink eye tracker. This method ensures that only valid trials, i.e. those where subjects follow the gaze restriction, are recorded and subsequently analysed.

As demonstrated in the previous sections, peripheral vision is identified as one of the fundamental factors that influence the perception of line segments, in particular if attentional processes are involved. In order to understand line segment perception, it is regarded a promising approach to consider position assessment first. Data acquired in Experiment E0, which requires subjects to assess the positions of markers presented in various regions of eccentricity, is intended to yield valuable contributions to the understanding of the processes involved in line segment assessment (see Chapter 4) – investigated in Experiments E1 and E2, and again, later, in Experiments S1 and S2. The following sections describe the experimental method for Experiment E0 in detail based on the methodological preliminaries that were established in Chapters 3 and 4.

5.1 Method

5.1.1 Subjects

The subjects were fifteen experimentally naive students – eight male and seven female – from the University of Bielefeld. Their average age was 26.8 years. All subjects had normal or corrected-to-normal vision and no pupil anomalies. The subjects were paid for their participation in the experiment.

5.1.2 Stimuli

The stimulus pictures were presented on a computer screen with a spatial resolution of 1280×1024 pixels ($39.0^o \times 29.4^o$ of visual angle). A fixation point with 0.2^o of visual angle in diameter was displayed at the center of each picture. The stimulus position marker was presented at a pseudo-random location (see Section 4.1.2), determined by its eccentricity region I–IV and its meridial segment (horizontal or vertical) relative to the fixation point. The position marker had a "+" shape, both the horizontal and the vertical bar constituents measured 0.4^o of visual angle in length. The fixation point and the position marker were dark grey in colour with their RGB-values set to $(R, G, B) = (100, 100, 100)$ and were presented on a light grey background with its RGB-values set to $(R, G, B) = (180, 180, 180)$. The choice of a light grey background colour proved to reduce reflections on the display monitor to a minimum which may have had a facilitatory effect on the position assessment. Figure 5.1 shows a typical stimulus picture.

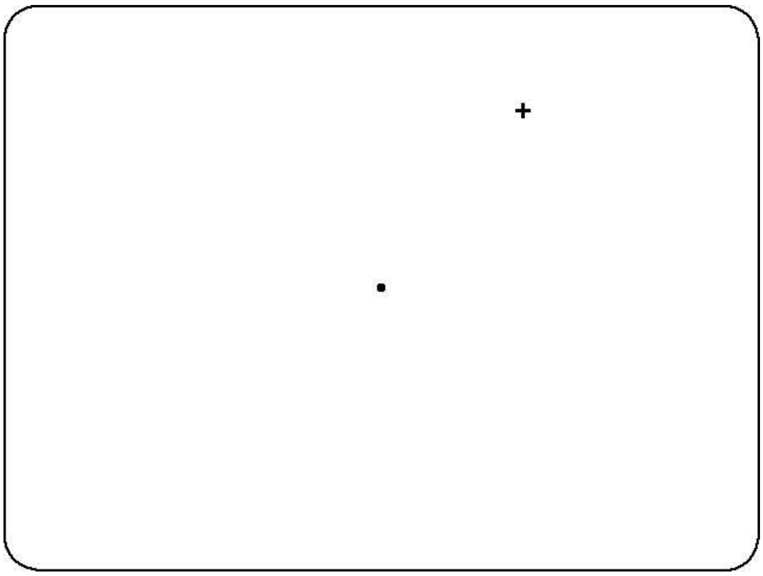


Figure 5.1: Typical stimulus picture in Experiment E0. Subjects had to assess the position of the target marker ("+") while observing the central fixation point.

5.1.3 Apparatus

The experiment took place in the eye tracking laboratory of the Neuroinformatics Group at the University of Bielefeld. The laboratory was artificially illuminated by ceiling-mounted, indirect light sources that yielded homgeneous lighting conditions. The stimuli were presented on a 19" colour computer monitor with a cathode-ray tube (CRT) display. The subjects were seated at an approximate distance of 50–60 cm from the display. The wall to the back of the subjects was covered with matt, black cloth to reduce reflections on the stimulus display. Eye movements were monitored using the SMI EyeLink eye-tracker system during the presentation of the peripheral target stimulus.

5.1.4 Procedure

All subjects were tested individually. Prior to the start of the experiment, they were provided with written instructions explaining the task they had to complete. Next, the eye tracker was set up and calibrated for each subject. To complete the calibration procedure, subjects had to look at nine dots that successively appeared at specific locations on the display.

Each trial of the experiment began with the presentation of the fixation point at the center of the screen (Frame 1, see Figure 5.2). 1000 ms after fixation point onset, the "+"-shaped target stimulus appeared in one of the eccentricity regions I-IV (Frame 2). The instructions required the subjects to assess the target marker position as accurately as possible without foveating it. Instead, the subjects had to focus on the central fixation point. If this restriction was violated and the eye tracker measured a gaze position outside the region of 1^o around the fixation point, a buzzer sounded and the trial was aborted. When subjects had successfully finished the assessment task and memorised the perceived position of the target marker, they pressed the left button of a computer mouse. A blank screen was displayed for 500 ms (Frame 3).

Next, the fixation point reappeared (Frame 4). After 300 ms, the comparison position marker was superimposed on it (Frame 5). The comparison marker had the same shape ("+") and dimensions as the previously shown target marker. Subjects were then

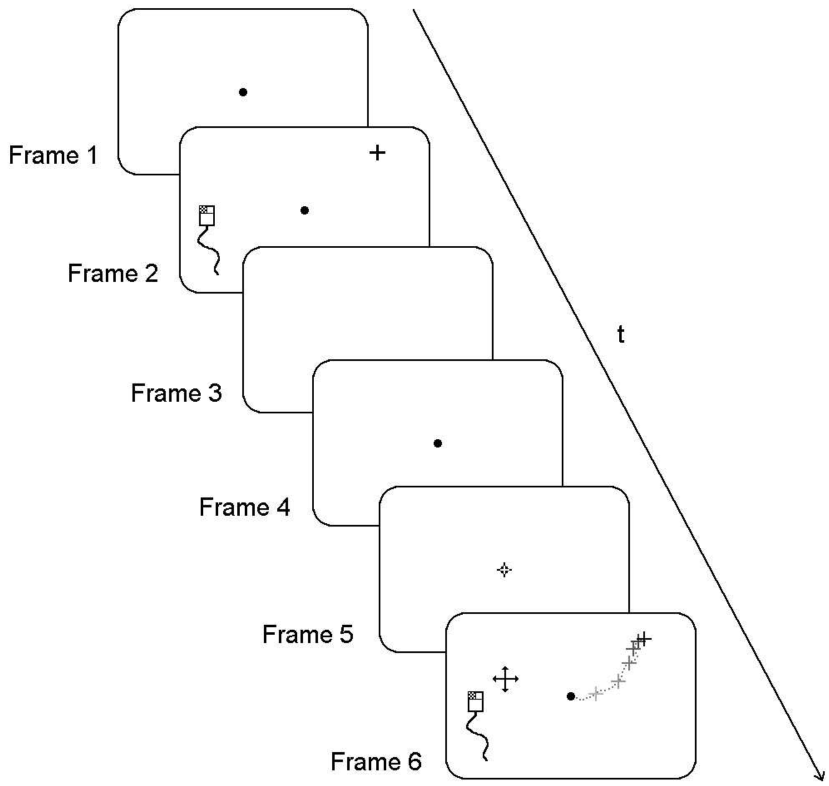


Figure 5.2: The sequence of procedural steps for a trial of Experiment E0. Frame 1: Fixation point. Frame 2: Target marker assessment. Frame 3: Blank screen. Frame 4: Fixation point. Frame 5: Comparison marker. Frame 6: Adjustment of comparison marker.

instructed to move the comparison marker using the computer mouse to the exact position where they originally perceived the target marker. When subjects moved the target away from the starting position, the fixation point remained at the center of the display as a point of reference (Frame 6). Once subjects had moved the comparison marker to its final position coinciding with their memorised target marker position, they pressed the left button of the computer mouse to confirm their adjustment and to start the next trial. The completion of this task did not require focussing on the fixation point, but allowed the gaze to move freely across the whole screen. Figure 5.2 illustrates the sequence of procedural steps for one trial.

The eye tracker was recalibrated after every trial in order to compensate for the headset becoming displaced due to head movements. Subjects had to fixate a single calibration marker at the center of the display to accomplish this "drift correction". The frequent recalibrations were necessary as the measurement of eye movements in such a setting requires extremely high accuracy. The region around the fixation point where eye movements are allowed is very small – 2^o of visual angle in diameter – so that even a minor misalignment of the headset might result in eye gaze positions that are evaluated as "out of bounds", even though they might in fact still be within the allowed region. Thus, frequent recalibration prevents subjects from being irritated by potentially unmotivated abortions of trials.

Subjects viewed a total of 360 stimulus pictures during the experiment, each possible combination of the four position eccentricities and the two meridial segments was displayed 45 times. Ten practice trials were conducted prior to the experimental trials in order to accustom the subjects to the eye-tracker headset, the experimental task and, in particular, the gaze-restricted viewing conditions.

5.2 Results

The eye tracker was only used in this experiment as a monitoring device to control the gaze restrictions imposed on subjects in the assessment phase of the peripherally presented target position marker. The eye-gaze data recorded here does not provide any valuable contribution to the understanding of the assessment process and will consequently not be analysed.

During the subsequent phase of adjustment of the comparison marker, the execution of eye movements could be expected as the gaze restriction did not apply any more. Although the visual strategy pursued in the adjustment phase was not the prime interest of this investigation, we consider it worthwhile to at least informally introduce two respective options. The first possible strategy could see subjects that continue fixating the center of the display while peripherally adjusting the comparison marker – i.e they do not actually execute eye movements. The idea here might be that the preservation of the viewing conditions and the possibility of matching the comparison with some sort of an after-image of the target stimulus facilitates the adjustment. However, the analysis of eye-movement data does not support this strategy, but favours an alternative approach. This second strategy suggests that the subjects' gaze guides the comparison marker movements and, vice versa, that the current marker position provides feedback to the eyes on the progress of the adjustment. Indeed, subjects seem to follow this second strategy.

As a consequence, we will not further analyse this eye-movement data, which obviously experiences interference from the adjustment procedure when the comparison marker is moved across the screen. Eye-movement data is mainly influenced by the marker movement – which suggests a smooth pursuit tracking eye-movement "mode" – rather than by the previous peripheral viewing condition. Certainly, this renders an interpretation difficult – or impossible – with regard to the effects of eccentricity on position assessment acuity. Instead, only the conventional psychophysical data, measured in the dependent variables as discussed in Section 3.4.2, are entered in an analysis of variance. The influence of the factors eccentricity region and meridial position is tested on the dependent variables reaction time RT, radial deviation DX, tangential deviation DY and Euclidean deviation DXY of the comparison marker position from the target marker position in a two-factorial analysis of variance. For all subsequent analyses of variance the α-level for the significance of effects is set to $p = 0.05$.

5.2.1 Dependent Variables

Reaction Time RT

Figure 5.3 (left) shows a histogram of all measured reaction times RT that subjects required in order to assess the position of the target marker under restricted gaze. The relative frequencies are charted irrespective of the eccentric and meridial locations of the target marker. RT varies from a minimum of 155 ms to a maximum of 3100 ms, with approximately 95% of the measured reaction times lying within the interval of 250 to 1350 ms. The histogram peaks at approximately 410 ms and subjects needed 662.1 ms on average to assess the marker position. A suitable fitting function would be asymmetrical (e.g. the χ^2 distribution or the Gamma-function (for details see Section 12.3)) with a positive skewness of +1.98.

In order to test the influence of the factors eccentricity and meridial position of presentation, RT is subjected to an analysis of variance. This detailed analysis of reaction times reveals a significant effect of the region of eccentricity on RT ($F(3; 42) = 9.88; p < 0.001$): The assessment of the target marker position took increasingly longer from Eccentricity I (624.9 ms) to Eccentricities II (652.8 ms), III (662.2 ms) and IV (696.3 ms). Furthermore, a post-hoc comparison of means using the Newman-Keuls test (for details see Hochberg & Tamhane, 1987; Toothaker, 1991; Glass & Hopkins, 1996) is computed. For this and subsequent post-hoc comparisons of means the α-level for critical ranges is set to $p = 0.05$. It reveals that no significant difference in RT exists between the two parafoveal Eccentricities II and III ($R_{crit} = 26.618; p = 0.321$) whereas RT significantly differs between all other eccentricity regions: ($R_{crit} = 32.125; p = 0.034$) for the comparison of RT between the Eccentricities I and II, ($R_{crit} = 33.010; p = 0.013$) for I vs. III, ($R_{crit} = 36.451; p < 0.001$) for I vs. IV, ($R_{crit} = 35.432; p = 0.005$) for II vs. IV and ($R_{crit} = 32.578; p = 0.024$) for III vs. IV. No significant main effect on

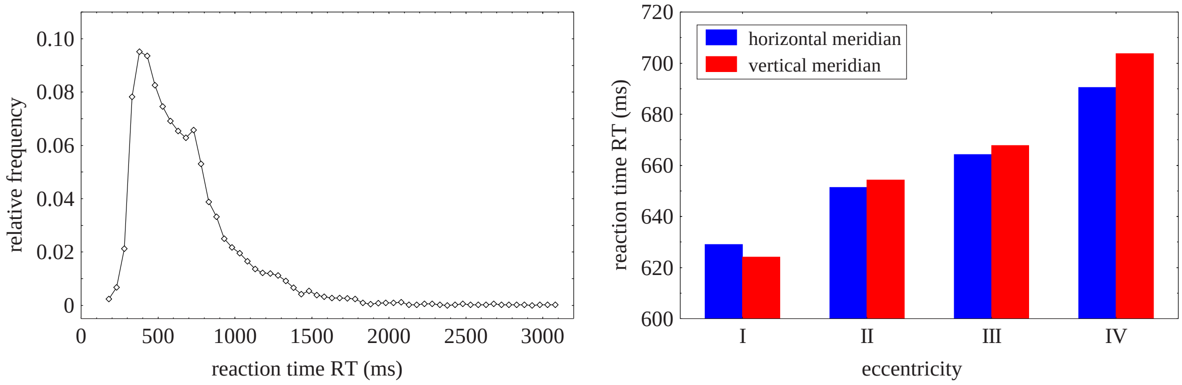


Figure 5.3: Left: Relative frequency distribution of reaction times RT, aggregated over all eccentricity regions and all meridial marker positions. Right: Reaction time RT as a function of eccentricity when position markers are presented either along the horizontal or the vertical meridian.

RT can be established for the meridial position factor ($F(1;14) = 1.68; p = 0.215$). Interaction effects of eccentricity and meridial position on RT are not significant either ($F(3;42) = 0.53; p = 0.661$). Figure 5.3 (right) shows the reaction time RT as a function of eccentricity and the meridial position of the target marker.

Positional Deviations DX, DY and DXY

The analysis of the mislocation of the comparison marker, relative to the target marker, i.e. the radial as well as the tangential and the Euclidean deviations of the comparison marker position from the target marker position can be accomplished by using one of two possible data sets: Either the *absolute* (positive) deviations from the target or a deviation measure that takes into account the *direction* of the deviation as well. As results are quite different for both data sets, the choice of the respective set has to be considered carefully with regard to the intended further employment of the findings and interpretation.

The relationship between the target and the comparison marker positions in terms of radial, tangential and Euclidean deviation was already discussed in Section 3.4.2 and is again illustrated in Figure 5.4. If we consider the "directional" data, the radial deviation DX will be assigned a *positive* value in case the radial coordinate of the comparison marker position has a greater value than that of the target marker position, i.e. when the radial position of the target marker is *"overestimated"*. Accordingly, DX will be negative when the radial coordinate of the comparison marker is closer to the fixation point than that of the target marker, i.e. when the radial position of the target marker is *"underestimated"*.

Regarding the tangential deviation, we determine DY as positive when the tangential coordinate of the target marker position has to be shifted clockwise – rotation of the radial axis around the fixation point – to match that of the comparison marker, and negative when shifted counter-clockwise. Here, it obviously does not make sense to classify the deviations as "overestimation" or "underestimation".

The Euclidean deviation DXY is assigned a positive value if the Euclidean distance

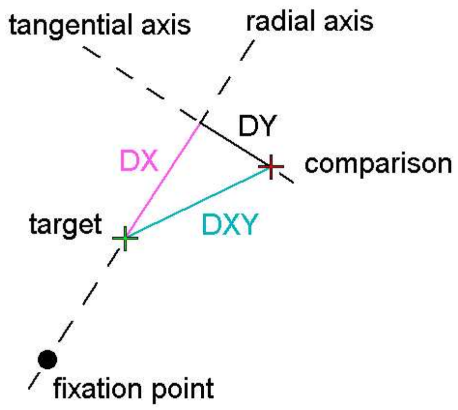


Figure 5.4: Radial and tangential axes and the respective deviations DX (pink) and DY (black) of the comparison marker from the target marker. DXY (light blue) denotes the Euclidean distance between the target (green) and the comparison marker (red).

between the fixation point and the comparison marker is greater than that between the fixation point and the target marker – and negative otherwise. Figure 5.4 thus shows a configuration where all DX, DY and DXY are positive. The "absolute" data sets ignore the directional information and are represented by the positive deviations only, i.e. directional and absolute data would be identical for the sample scenario in Figure 5.4.

As we will later be interested in modelling the distribution of the positional assessments of the target, information from both data types is required. If the distribution is thought of as being bivariate in nature, the analysis of directional data yields information on the origin and the orientation of the distribution whereas the distributions "extent" can be more reliably determined through the absolute data – this is particularly true for symmetric distributions such as the normal distribution. The following paragraphs detail the results for DX, DY and DXY when both absolute and directional analyses are performed.

Absolute Radial Deviation DX_p

Let us first consider the absolute radial deviation DX_p. As the case with reaction time RT before, we enter DX_p into a two-factorial analysis of variance in order to test the influence of the independent variables eccentricity and meridial position on the radial deviation. The results show that an increase of DX_p coincides with the target marker presentation in increasingly peripheral locations. The mean absolute radial deviations (all given in degrees of visual angle) measure 0.47^o for Eccentricity I, 0.79^o for Eccentricity II, 0.91^o for Eccentricity III and 1.06^o for Eccentricity IV. The standard deviations for DX_p are computed as 0.39, 0.62, 0.70 and 0.84^o for the Eccentricities I–IV, respectively. The differences between the eccentricity levels are highly significant ($F(3;42) = 1.37; p < 0.001$). A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between all eccentricity levels: ($R_{crit} = 0.149; p < 0.001$) for the comparison of DX_p between the Eccentricities I and II, ($R_{crit} = 0.147; p < 0.001$) for I vs. III, ($R_{crit} = 0.147; p < 0.001$)

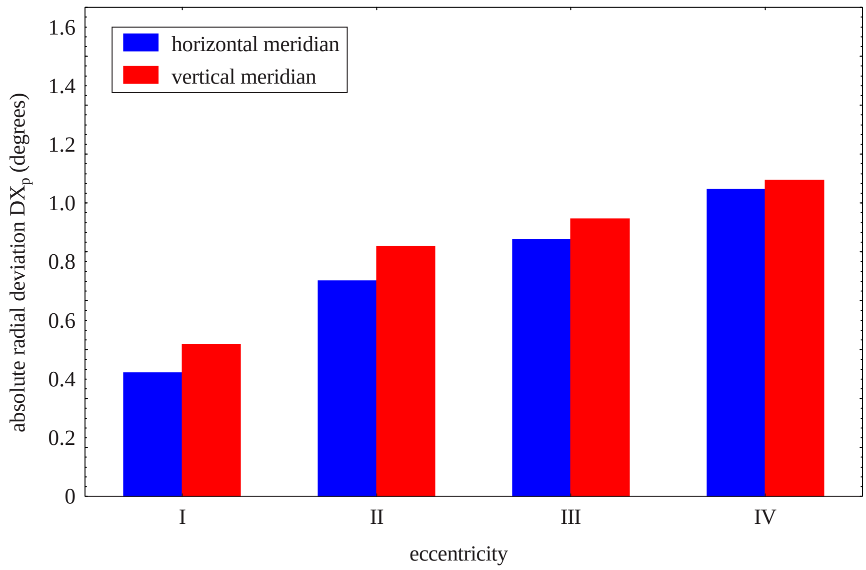


Figure 5.5: Absolute radial deviation DX_p of the comparison marker position from the target marker position for all eccentricities and meridial positions.

for I vs. IV, ($R_{crit} = 0.101; p = 0.040$) for II vs. III, ($R_{crit} = 0.142; p < 0.001$) for II vs. IV and ($R_{crit} = 0.128; p = 0.009$) for III vs. IV.

Again, no main effect for the meridial position can be observed ($F(1; 14) = 0.13; p = 0.070$). However, there appears to be a tendency towards less absolute radial deviation when the target markers are presented in proximity to the horizontal meridian than in proximity to the vertical meridian. Interaction effects of eccentricity and meridial position on DX_p are not significant ($F(3; 42) = 0.02; p = 0.663$). Figure 5.5 shows the mean absolute radial deviation DX_p as a function of eccentricity and meridial position of the target marker.

Absolute Tangential Deviation DY_p

Analogous to DX_p, the absolute tangential deviation DY_p is subjected to an analysis of variance. Similar to the previous findings, differences between the Eccentricities I–IV are highly significant for DY_p ($F(3; 42) = 3.26; p < 0.001$). A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between all eccentricity levels: ($R_{crit} = 0.071; p < 0.001$) for the comparison of DY_p between the Eccentricities I and II, ($R_{crit} = 0.067; p < 0.001$) for I vs. III, ($R_{crit} = 0.072; p < 0.001$) for I vs. IV, ($R_{crit} = 0.057; p < 0.001$) for II vs. III, ($R_{crit} = 0.064; p < 0.001$) for II vs. IV and ($R_{crit} = 0.070; p < 0.001$) for III vs. IV. The least tangential deviation is found for Eccentricity I (0.31^o) and then constantly increases for Eccentricities II (0.45^o), III (0.60^o) and IV (0.73^o). The standard deviations for DY_p are computed as 0.26^o, 0.36^o, 0.49^o and 0.59^o for the Eccentricities I–IV, respectively. The meridial position does not exert a significant effect on DY_p ($F(1; 14) = 0.10; p = 0.098$), but the tendency towards a more accurate assessment of absolute tangential position of the target markers in proximity to the horizontal meridian – compared with those presented in proximity to the vertical

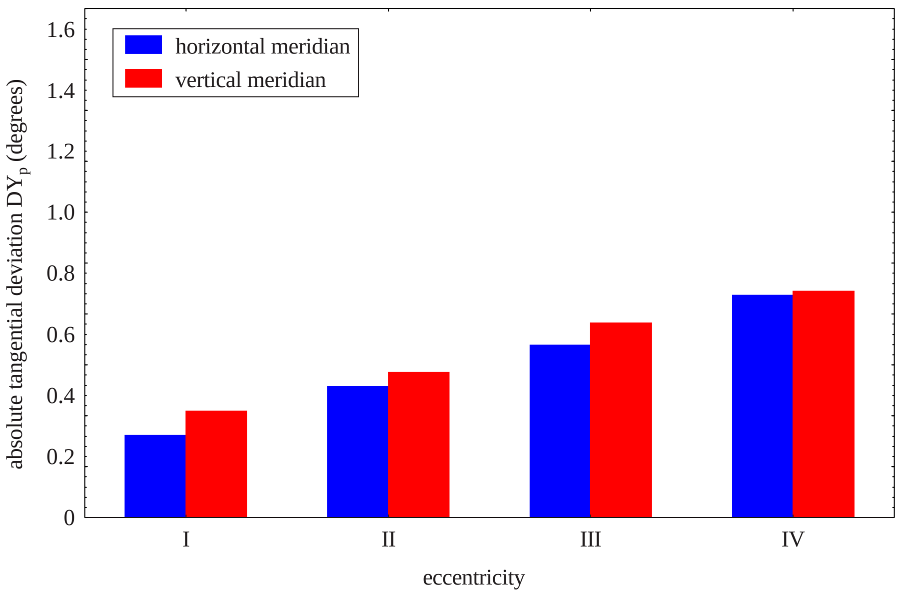


Figure 5.6: Absolute tangential deviation DY_p of the comparison marker position from the target marker position for all eccentricities and meridial positions.

meridian – prevails as for DX_p. No interaction effects between eccentricity and meridial position on DY_p can be observed ($F(3;42) = 0.03; p = 0.384$). Figure 5.6 illustrates the mean values of DY_p for the different peripheral regions and the meridial positions.

Qualitatively comparing the magnitudes of DX_p and DY_p already suggests that these two measures are significantly different from each other: The radial deviation is larger than the tangential deviation. When we enter the distinction between these two axes as an additional factor into the analysis of variance, the ad-hoc hypothesis is confirmed

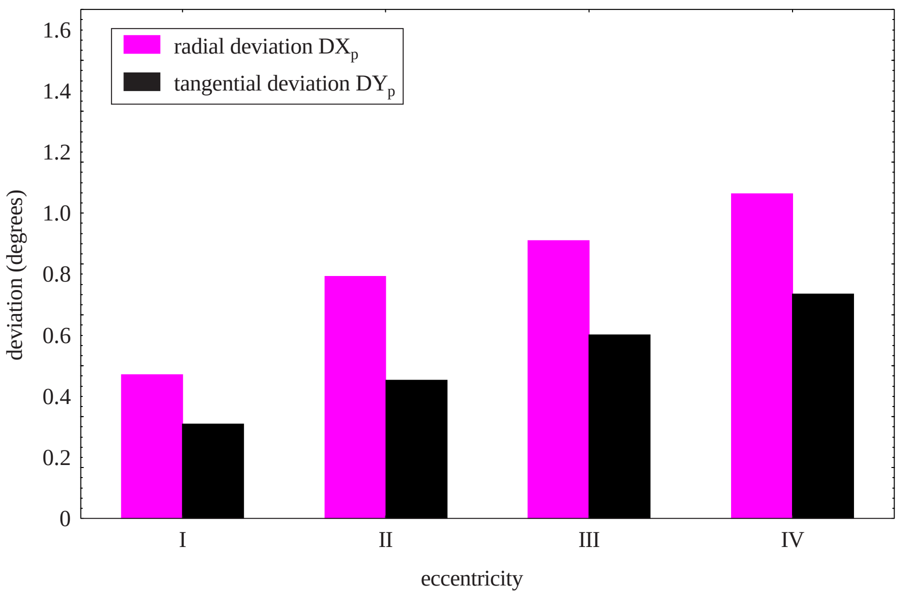


Figure 5.7: The absolute radial deviations DX_p and the absolute tangential deviations DY_p of the comparison marker position from the target marker position as functions of eccentricity.

$(F(1;14) = 1.04; p < 0.001)$. Figure 5.7 shows the means of DX_p in comparison with those of DY_p for all eccentricity regions I–IV, collapsed over the horizontal and meridial presentation positions.

Absolute Euclidean Deviation DXY_p

The Euclidean deviation DXY_p is the last dependent variable that is tested in Experiment E0 with respect to possible interactions with the peripheral and meridial presentation positions. DXY_p, which is computed from DX_p and DY_p as the Euclidean distance between the target and comparison marker positions, increases with increasing eccentricity. This highly significant effect $(F(3;42) = 2.37; p < 0.001)$ is manifested by mean values for DXY_p of 0.60^o for Eccentricity I, 0.98^o for Eccentricity II, 1.18^o for Eccentricity III and 1.40^o for Eccentricity IV. The standard deviations for DXY_p are computed as 0.40^o, 0.59^o, 0.70^o and 0.84^o for the Eccentricities I–IV, respectively. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences again exist between all eccentricity levels: $(R_{crit} = 0.153; p < 0.001)$ for the comparison of DXY_p between the Eccentricities I and II, $(R_{crit} = 0.153; p < 0.001)$ for I vs. III, $(R_{crit} = 0.158; p < 0.001)$ for I vs. IV, $(R_{crit} = 0.114; p = 0.001)$ for II vs. III, $(R_{crit} = 0.153; p < 0.001)$ for II vs. IV and $(R_{crit} = 0.160; p < 0.001)$ for III vs. IV.

In accordance with the results of the analyses of variance for DX_p and DY_p, a corresponding tendency towards an effect of the meridial position on DXY_p can be noted $(F(1;14) = 0.31; p = 0.064)$: The Euclidean deviation of the comparison from the target marker appears to be slightly less when the target marker is presented in proximity to the horizontal meridian. This tendency is qualitatively visible in Figure 5.8 where the Euclidean deviation DXY_p is shown as a function of eccentricity and the meridial position of the target marker. There is no interaction effect between eccentricity and meridial

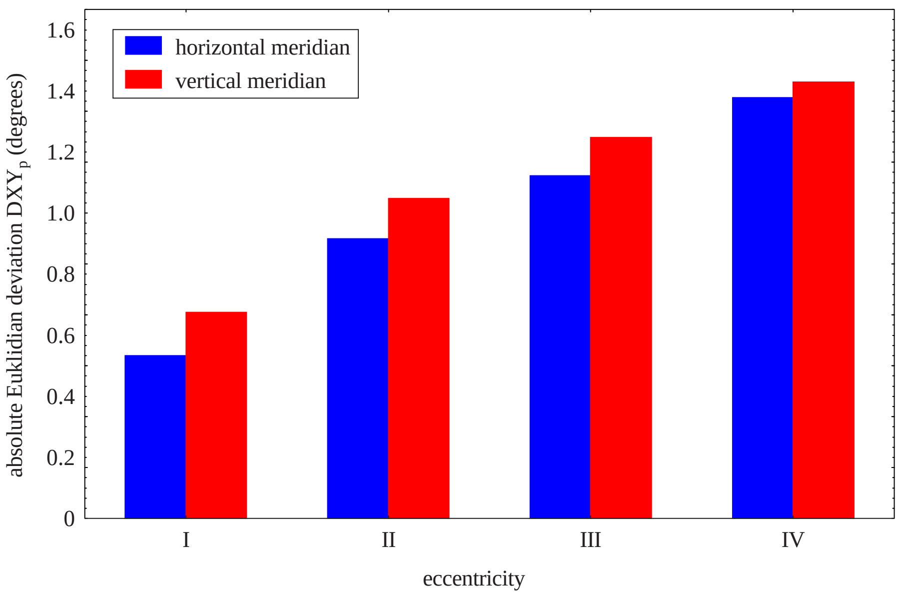


Figure 5.8: Absolute Euclidean deviation DXY_p of the comparison marker position from the target marker position for all eccentricities and meridial positions.

position on DXY_p ($F(3;42) = 0.02; p = 0.537$).

As already briefly mentioned, the distribution of the comparison marker positions – which can be thought of as sketched in Figure 5.9 (left) – requires more than just knowledge of the “extent” of the distribution. The origin of the distribution, i.e. its “anchor point”, for example, constitutes essential information for describing the distribution function. The analyses of DX_p, DY_p and DXY_p do not yield this data. Instead, an analysis of the “directional” data sets is required to obtain the direction of the deviation of the comparison marker relative to the target marker. These deviations will again be analysed separately for the radial (DX), tangential (DY) and Euclidean (DXY) dimensions. In Figure 5.9 (left), the green dot highlights the target marker position that the subjects had to assess, the black dots show all positions (for all subjects and repetitive measures by subjects) where they placed the comparison marker. The red dot marks the averaged comparison marker position. The ellipsis illustrates the results of a principal component analysis (PCA) that approximates the (orientation of the) distribution of the comparison marker positions. If the relative frequencies of assessment positions are also taken into account and charted on an axis perpendicular to the x–y–coordinate (paper) plane, a distribution shaped similarly to that shown in Figure 5.9 (right) emerges. The exact procedure will be discussed later in Chapter 8.

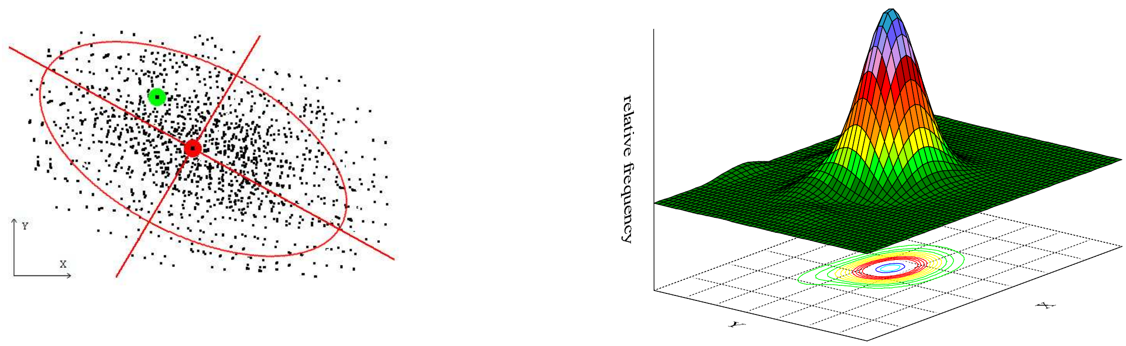


Figure 5.9: Left: Approximation of a sample distribution of comparison marker positions using principal component analysis (PCA). Right: Original distribution of the same comparison marker positions and their relative frequencies.

As the analyses of DX_p, DY_p and DXY_p revealed, the meridial position of the target marker does not have a significant effect on the absolute radial, tangential or Euclidean deviations of the comparison marker position from the target marker position. We will thus collapse the data over the factor meridial position and only test the effect of the eccentricity region on the “directional” deviations DX, DY and DXY.

Radial Deviation DX

An analysis of variance yielded a significant eccentricity effect on the radial deviation DX ($F(3;42) = 0.09; p = 0.048$) and the means for DX are computed to -0.17^o for Eccentricity I, -0.34^o for Eccentricity II, -0.37^o for Eccentricity III and -0.43^o for Eccentricity IV.

A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between almost all eccentricity levels: ($R_{crit} = 0.285; p = 0.012$) for the comparison of DX between the Eccentricities I and II, ($R_{crit} = 0.267; p = 0.021$) for I vs. III, ($R_{crit} = 0.255; p = 0.029$) for I vs. IV, ($R_{crit} = 0.267; p = 0.021$) for II vs. IV and ($R_{crit} = 0.284; p = 0.015$) for III vs. IV. Only when comparing DX between the eccentricity levels II and III the Newman-Keuls test does not produce a significant difference ($R_{crit} = 0.213; p = 0.065$).

Thus, for all eccentricities, subjects on average placed the comparison marker closer to the fixation point on the radial axis. The standard deviations for DX are computed as 0.59^o, 0.92^o, 1.08^o and 1.28^o for the Eccentricities I–IV, respectively. Figure 5.10 illustrates the means of the radial deviations DX for the Eccentricities I–IV.

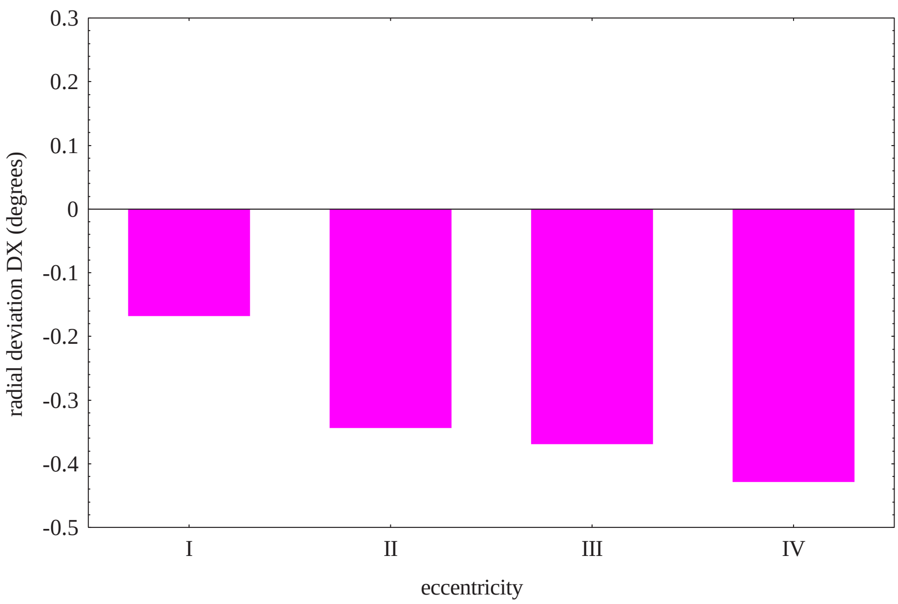


Figure 5.10: Radial deviation DX of the comparison marker position from the target marker position for all eccentricities, collapsed over the horizontal and vertical meridial locations.

Tangential Deviation DY

When the data for the tangential deviation DY is entered into an analysis of variance, a significant effect of eccentricity thereupon emerges ($F(3; 42) = 0.20; p = 0.002$). However, as the computation of means for the four eccentricities shows, no steady tendency for direction for the mislocation is visible. Means are -0.02^o for Eccentricity I, 0.02^o for Eccentricity II, -0.08^o for Eccentricity III and 0.02^o for Eccentricity IV. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist only between the following eccentricity levels: ($R_{crit} = 0.079; p = 0.003$) for the comparison of DY between the Eccentricities II and III and ($R_{crit} = 0.080; p = 0.003$) for III vs. IV. In contrast, differences between the eccentricity levels I and II ($R_{crit} = 0.059; p = 0.192$), between I and III ($R_{crit} = 0.067; p = 0.055$), I and IV ($R_{crit} = 0.062; p = 0.141$) and II

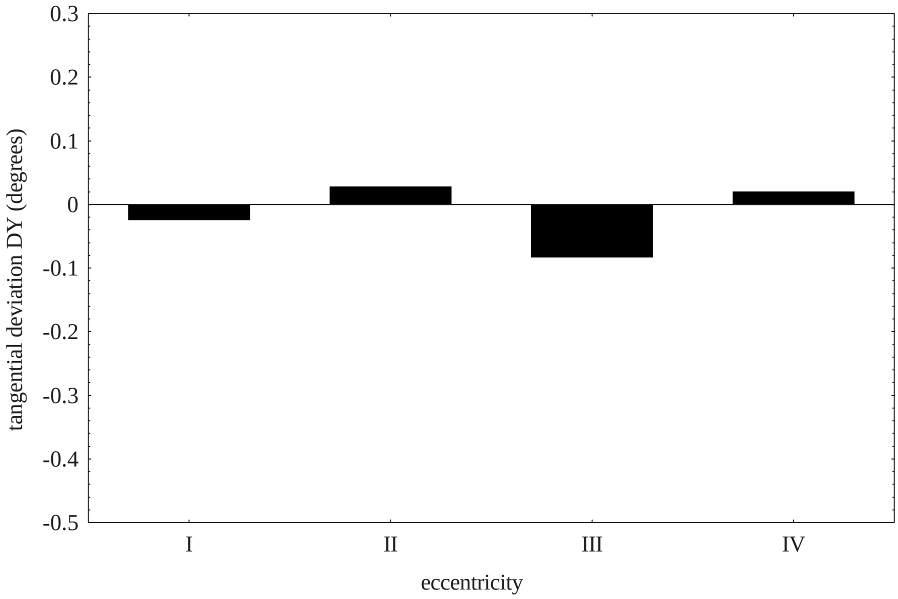


Figure 5.11: Tangential deviation DY of the comparison marker position from the target marker position as a function of eccentricity.

and IV ($R_{crit} = 0.040; p = 0.790$) are not significant.

The tangential deviations are significantly smaller than the radial deviations ($F(1; 14) = 0.30; p = 0.010$). The standard deviations for DY are computed as 0.41^o, 0.57^o, 0.78^o and 0.94^o for the Eccentricities I–IV, respectively. Figure 5.11 shows the means of the tangential deviations DY for the Eccentricities I–IV.

Euclidean Deviation DXY

The analysis of variance for the Euclidean deviation DXY yields a significant effect for the tested factor eccentricity ($F(3; 42) = 0.07; p = 0.039$). A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences again exist between all eccentricity levels: ($R_{crit} = 0.240; p = 0.026$) for the comparison of DXY between the Eccentricities I and II, ($R_{crit} = 0.220; p = 0.015$) for I vs. III, ($R_{crit} = 0.213; p = 0.010$) for I vs. IV, ($R_{crit} = 0.251; p = 0.045$) for II vs. III, ($R_{crit} = 0.251; p = 0.030$) for II vs. IV and ($R_{crit} = 0.256; p = 0.039$) for III vs. IV. The computed means are -0.15^o for Eccentricity I, -0.33^o for Eccentricity II, -0.38^o for Eccentricity III and -0.44^o for Eccentricity IV. The standard deviations for DXY are computed as 0.71^o, 1.06^o, 1.31^o and 1.57^o for the Eccentricities I–IV, respectively.

As could be expected from the result of the analyses of DX and DY, the greater magnitudes of the radial deviations – compared to the tangential deviations – dominate the Euclidean deviations and yield a steadily increasing Euclidean deviation with more peripheral target marker positions. The negative values of DXY account for the fact that subjects positioned the comparison markers closer to the fixation point than where the target markers were located. Figure 5.12 illustrates the means of the Euclidean deviations DXY for the Eccentricities I–IV.

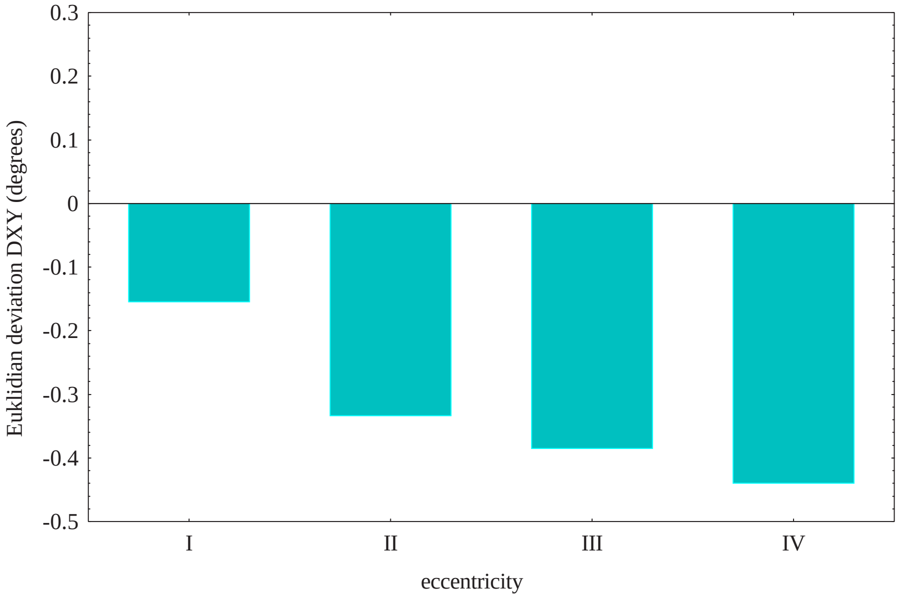


Figure 5.12: Euclidean deviation DXY of the comparison marker position from the target marker position as a function of eccentricity.

5.3 Discussion and Conclusions

After the quantitative analysis of the data recorded in Experiment E0 in the previous section, we will now discuss the results with particular respect to their implications for the following Experiments E1 and E2 that research line segment length and orientation. The discussion will also be guided by the intention to model the location assessment results so that they can be used to simulate the experimental data obtained in Experiments E1 and E2.

Let us briefly recall which independent variables were tested to influence which dependent variables in Section 5.2: The factors meridial position and eccentricity were systematically varied and we analysed these effects on the dependent variables reaction time RT, radial deviation DX (and DX_p), tangential deviation DY (and DY_p) and Euclidean deviation DXY (and DXY_p) of the comparison marker position from the target marker position. How can we now interpret these various interactions and what do they imply? The two most fundamental observations the findings yield are that

1. the factor meridial position does *not* exert a significant effect and

2. the factor eccentricity exerts a significant effect

on the dependent variables. Whereas the second observation might be expected, the lack of an effect of the position of the target relative to the fixation point, either along the horizontal or the vertical meridian, comes as a surprise. But, let us have a look at the various observations in detail.

Due to the viewing restriction imposed on the subjects, their gaze must remain more or less stationary during the position assessment. The voluntary, controlled execution of saccades within the allowed range of 1^o from the central fixation point is almost impossible, particularly when the task requires "covert" attention to a peripheral location. Indeed, the eye-movement data shows that in most cases only a single fixation was recorded, so that for the given scenario the fixation duration coincides with the reaction time RT. When we now take into account that, under normal viewing conditions when the gaze is not restricted, eye fixations approximately last between 150 and 400 ms, it is quite "natural" that the values measured here for RT are quite low. Even without the special requirements of the task here, it is a rather difficult task for subjects to accomplish extremely long fixations. Consequently, only very few values of RT exceed 1350 ms and were measured on the rare occasions when subjects managed to execute more than just one fixation within the allowed range around the fixation point – although it is known from aftereffect experiments that subjects are able to fixate a particular point for about 30 seconds. For the present task, however, subjects obviously extend fixation durations to only such a degree that still does not present too great a (concentration) effort and, on the other hand, does not – at least in their own belief – compromise too much their performance in the assessment of the target marker location.

Certainly, the further the target marker is moved out to the periphery of the fixation point, the more difficult the assessment of the marker position becomes. Although subjects obviously do not feel very comfortable executing long fixations, they try to compensate for the increased difficulty of the task by an increase of RT. This may be understood when discussed in the context of mental rotation experiments where reaction time was found to increase for larger angles between two (target and comparison) stimuli. In the present scenario, the task may be considered a *"mental translation"*. In analogy to mental rotation, longer translation distances may require more time to accomplish stimulus assessment. This could possibly explain the increase of RT in more peripheral regions in this experiment.

An interesting finding, which the analyses of the other dependent variables – at least partially – support, is that the difference between RT for Eccentricity II and Eccentricity III is considerably smaller than the differences between the other adjacent eccentricity regions, although the boundaries between the eccentricity regions are all spaced at equally distant intervals. We recall the original definition of both the Eccentricities II and III as belonging to the parafoveal region, as the range of this region (from 3^o to 10^o) appeared to be too large to be accounted for by only a single level of the factor eccentricity in these studies. Although the marker position in Eccentricity III still takes longer to be assessed than in Eccentricity II, the respective RTs are not found to differ significantly. This observations could be interpreted as *supporting the classification of peripheral viewing in foveal, parafoveal and peripheral perception regions.* In addition, it could give rise to the hypothesis that the perception effort (in terms of RT) *within* each eccentricity region does not vary considerably or is possibly even invariant and that differences are most pronounced around the designated *boundaries* of these eccentricity regions. However, if we consider a physiological approach that attributes the differences to a decrease in receptor density in the retina, this density drops rapidly from the fovea to the periphery, but does not show obvious plateaux that could account for three explicit eccentricity levels. Maybe a detailed review of the finer structures in the topology of the retinal receptors or the respective cortical areas could produce evidence for or against such a link.

What these physiological properties and the findings regarding RT certainly do not imply, is, of course, that sharp boundaries exist to separate the foveal from the parafoveal, and the parafoveal from the peripheral region. On the basis of the analysis of RT alone, a distinction between three levels (foveal, parafoveal and peripheral) and the choice of boundaries between them as accomplished in our studies appear nevertheless sensible.

In contrast to the effect of eccentricity on reaction time, the lack of significant differences in RT for the two meridial positions (horizontal vs. vertical, relative to the fixation point) can be considered a first indicator that no such differences exist in the other dependent variables either – which is indeed the case. Alternatively, we could also have concluded that subjects were just not aware that one of the meridial configurations would be more difficult to assess than the other, but then find significant differences in the positional deviations $DX_{(p)}$, $DY_{(p)}$ and/or $DXY_{(p)}$.

However, the analyses of the deviations suggest *no influence of the meridial position* on those variables. Although we noticed this effect – or rather that such an effect does not exist – for RT, it is again surprising to find no such effect for the positional deviations either. Whether the marker's position has to be assessed when it is presented in proximity to the horizontal or to the vertical axis does not obviously result in significant differences within either DX, DY or DXY. Specifically, targets' positions along the vertical meridian can be as accurately judged as those along the horizontal meridian.

We would certainly not have expected this observation initially. First, we must consider that the retina is not a true hemisphere, but ellipsoidal in shape with the horizontal axis being the longer. Furthermore, with binocular viewing, the visual field is ovoid, its horizontal axis being approximately 0.5 times greater than its vertical axis (Prinzmetal & Gettleman, 1993). Taking this asymmetry into account, the preferred horizontal orientation of the visual field and the further range of receptors along this axis could be well expected to lead to a better position assessment accuracy along the horizontal than along the vertical meridian. Instead, the tendencies towards an interaction in the analyses of DX, DY and DXY in Experiment E0 only slightly hint at such a dependence. It must be taken into account, however, that the assessment is probably based on the cortical rather than the retinal representation. The *retinal information may thus be corrected* in subsequent processing steps as to compensate for the retinal distortion. This apparently yields *cortical* position representations which are *equally accurate for all meridial positions* of the stimulus marker.

Contrary to the missing meridial position effect, the significantly increasing assessment error with increasing eccentricity could be expected. The rise of all absolute deviations DX_p, DY_p and DXY_p the further the target is being presented from the fixation point can be attributed to the poorer spatial resolution in the peripheral visual field (e.g. Thompson & Fowler, 1980). This again is an integral part of Tsal's (1999) concept of different metrics for attended and unattended stimuli. Even though advanced by Tsal for length estimation (cf. Section 2.2), the idea of metrics composed of fine units for attended judgement – resembling high spatial resolution in foveal viewing due to the retinal anatomy with high central receptor density – and of coarse units for unattended judgement – resembling low(er) spatial resolution in peripheral viewing – appears appealing for visual localisation as well. Targets that are presented foveally or in near-foveal regions, for example in eccentricity region I, can be explicitly visually *attended*. This can be achieved without the execution of eye movements, which are not permitted in this experiment, and thus allows for fine judgements with respect to the target position. In consequence, this leads to a fairly accurate position assessment. In contrast, targets presented in more eccentric regions, such as in the eccentricity regions II, III and IV, cannot be directly visually attended. The then only coarse position judgement of these unattended stimuli produces less accurate results with a greater variance or standard deviation – as observed in Experiment E0.

Some specific observations require clarification in this discussion with regard to the separate analyses for the radial deviation $DX_{(p)}$, the tangential deviation $DY_{(p)}$ and the Euclidean deviation $DXY_{(p)}$. Thus, the comparison between the absolute deviations DX_p and DY_p reveals that the tangential position of the target marker can be far better assessed than the radial position. In other words, it appears to be much easier for subjects to correctly judge the *direction* of the marker relative to the fixation point – which can be seen as corresponding with the tangential position – than to correctly judge the *distance* between the fixation point and the marker – corresponding with the radial position. This is shown in DX and DY – the two variables that take into account the direction of the respective deviations – even more explicitly than in the absolute deviations DX_p and DY_p. Here it can be clearly seen that, on average, there is hardly any systematic deviation of the comparison from the target position in the tangential direction. Furthermore, this judgement is achieved more or less independently of the eccentric position. However, the increase in standard deviations with increased peripheral presentation indicates that the tangential position can be judged with less precision under eccentric viewing conditions, although no specific directional effect, i.e. clockwise or counter-clockwise from the original tangential position, prevails.

On the other hand, the radial deviation DX exhibits a *directional effect*, the distance between fixation point and target marker position is increasingly *underestimated* with increasing eccentricity. The uncertainty along the radial axis, which might be termed *"eccentricity axis"* as well, seems to be greater than along the tangential axis and it appears that with increasing eccentricity the axis *"contracts"* so that *distances appear closer than they actually are*. This could possibly be caused by mapping the same distance on fewer receptors in the peripheral than in the more central visual field. If this is not compensated for by other mechanisms – which is obviously not the case – the *distance perceived in the periphery will be judged shorter*. The fact that the distance judgement along the eccentricity axis is characterised by constantly changing receptor densities – which decrease with increasing eccentricity – does not facilitate the computation either. (It must be noted, however, that the receptor density decreases much stronger than the observed underestimation effect and can thus probably not alone account for this effect.) The fact that the tangential ("direction") assessment of the target marker does not have to account for such changes – as being computed along the axis perpendicular to the eccentricity axis –

might motivate the better performance in tangential position judgement.

These results suggest that the assessment of position is governed by *two distinct processes*. The first process is responsible for the assessment of the *direction* in which the target in question is situated, a process that obviously works quite *accurately* and more or less *independently of the peripheral position* of the target. The second process determines the *distance* between fixation point and target. This process yields less accurate judgements as the *radial position* of the target is significantly *underestimated*. Furthermore, this process is *eccentricity dependent*. On aggregate, the combination of these two processes yields positional judgements that are *dominated by the distance component and results in a perceived position of the target marker that is shifted towards the fixation point, but shows very little directional divergence*.

The following chapters will now address the perception of the next more complex, higher dimensional stimulus type, namely *line segments*, under the same peripheral viewing conditions as in Experiment E0. First, the assessment of line segment lengths will be discussed.

Chapter 6

Experiment E1: Length Assessment in Peripheral Vision

In the second experiment (Experiment E1) in this series of three experiments that aim to establish and quantify the effects of eccentric stimulus presentation on the perception and assessment of specific stimulus dimensions, we investigate line segment length. The "reference" data obtained in this experiment allows for the testing of the existence of correlations between the assessment error of peripherally perceived lengths of line segments and the mislocation of marker positions. If a correspondence can be found, this would indicate that observations in this experiment can possibly be attributed to mechanisms that were identified to influence location assessment. The peripheral assessment of line segment length might thus be *decomposed* and could be accomplished by peripherally assessing the locations of the end points of the line segment. The distance between the end points then yields the line segment length.

The following sections describe the experimental method for Experiment E1, based on the methodological preliminaries that were established in Chapters 3 and 4. Subsequently, the results will be presented and discussed which allows us to draw conclusions about the mechanisms that may govern peripheral length perception.

6.1 Method

6.1.1 Subjects

The subjects were twelve experimentally naive students – six male and six female – from the University of Bielefeld. Their average age was 27.5 years. All subjects had normal or corrected-to-normal vision and no pupil anomalies. The subjects were paid for their participation in the experiment.

6.1.2 Stimuli

As in Experiment E0, the stimulus images were displayed on a computer screen with a spatial resolution of 1280x1024 pixels. At the center of each picture a fixation point

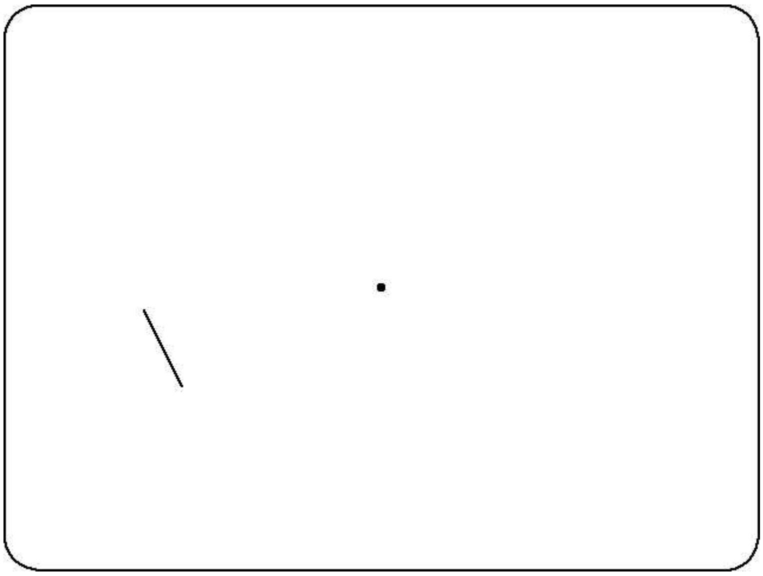


Figure 6.1: Typical stimulus picture in Experiment E1. Subjects had to assess the length of the target line segment while observing the central fixation point.

was displayed with 0.2^o of visual angle in diameter. The stimulus target line segment was presented at a pseudo-random location so that it lay entirely within one of the eccentricity regions I–IV (see Section 4.1.2). The target line segment had a thickness of one pixel (0.03^o), an orientation of either $0^o \pm 22.5^o$ ("horizontal"), $45^o \pm 22.5^o$ or $135^o \pm 22.5^o$ ("oblique") or $90^o \pm 22.5^o$ ("vertical") and a length of either $1^o \pm 0.3^o$ ("short"), $4^o \pm 0.3^o$ ("intermediate") or $7^o \pm 0.3^o$ ("long") of visual angle (see Section 4.1). The fixation point, the target line segment and the background were set to the same dark and light grey colours, respectively, as in Experiment E0. Figure 6.1 shows a typical stimulus picture.

6.1.3 Apparatus

The apparatus used was the same as in Experiment E0.

6.1.4 Procedure

The procedure varied from that implemented in Experiment E0 only insofar, as subjects were asked to assess the *length of the target line segment* presented in one of the eccentricity regions I-IV without foveally looking at it. Again, the gaze was restricted to a region of 1^o around the central fixation point (Frame 1) and this contingency was monitored by the eye tracker. When subjects had successfully finished the assessment task and memorised the perceived length of the target line segment, they pressed the left button of the computer mouse (Frame 2). Subsequently, a blank screen was shown for 500 ms (Frame 3) and the fixation point reappeared (Frame 4) for 300 ms.

The fixation point was then replaced by the comparison line segment (Frame 5), the line segment center being located at the center of the screen. The comparison line segment had the same dimensions as the previously shown target line segment with respect to

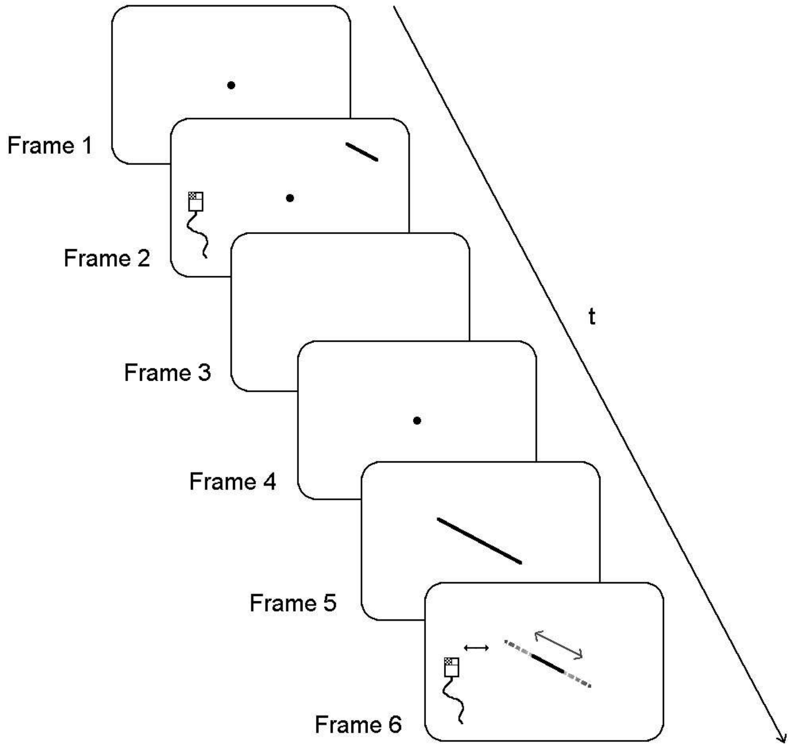


Figure 6.2: The sequence of procedural steps for a trial of Experiment E1. Frame 1: Fixation point. Frame 2: Target line segment length assessment. Frame 3: Blank screen. Frame 4: Fixation point. Frame 5: Comparison line segment. Frame 6: Adjustment of comparison line segment length.

thickness, colour and orientation. However, the length of the comparison line segment was set to a random value within the range of 0.03^o to 20.0^o. The subject was instructed to adjust the length of the comparison line segment using the computer mouse so that it exactly matched the memorised perceived length of the target line segment (Frame 6). Moving the mouse to the left resulted in a decrease in the length of the comparison line segment and moving the mouse to the right resulted in an increase in length. A press of the left mouse button confirmed the length adjustment and started the next trial. During this adjustment phase, subjects could move their gaze freely across the whole screen. Figure 6.2 illustrates the sequence of procedural steps for one trial.

Subjects viewed a total of 360 stimulus pictures during the experiment, so that each possible combination of the four position eccentricities, the three orientations and the three lengths was displayed ten times. Ten practice trials were conducted prior to the experimental trials.

6.2 Results

In comparison with Experiment E0, the choice of stimuli and the procedural design require a slightly altered analysis of data. Rather than the previous two-factorial analysis of variance, data is now subjected to a three-factorial analysis of variance in order to account for the three independent variables of eccentricity region, target line segment length and orientation. The effects of these factors are tested on the dependent variables reaction time RT and the length deviation DL of the comparison line segment from the target line segment.

6.2.1 Dependent Variables

Reaction Time RT

The relative frequencies for RT are distributed in Experiment E1 almost identical to the distribution of reaction times RT measured in the previous experiment. The measured reaction times range from a minimum of 156 ms to a maximum of 3976 ms. The overall mean RT, averaged over all values, is computed at 660.7 ms and the histogram peaks at 430 ms. As before, an asymmetrical function with a positive skewness of +1.98 would be appropriate to fit the distribution of RT. Approximately 95% of the values lie within the interval of 250 to 1450 ms. Figure 6.3 (left) shows the respective histogram for RT.

As in the previous experiment, the factor eccentricity exerts a significant effect on the reaction time RT required for the assessment of line segment lengths ($F(3;33) = 4.54; p = 0.009$). The mean RT increases from 640.1 ms for Eccentricity I, through 655.3 ms and 671.0 ms for the Eccentricities II and III, to 683.2 ms for Eccentricity IV. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between the following eccentricity levels: ($R_{crit} = 32.198; p = 0.039$) for the comparison of RT between the Eccentricities I and III, ($R_{crit} = 37.514; p = 0.012$) for I vs. IV, ($R_{crit} = 30.992; p = 0.047$) for II vs. III and ($R_{crit} = 35.672; p = 0.035$) for II vs. IV. In contrast, only tendencies for the existence of significant differences in RT can be found between the Eccentricities I and II ($R_{crit} = 25.401; p = 0.080$) and between the Eccentricities III and IV ($R_{crit} = 27.941; p = 0.078$).

Both target line segment length and orientation factors do not show a significant main effect on RT, the analysis of variance yields ($F(2;22) = 1.00; p = 0.383$) and ($F(2;22) = 2.50; p = 0.125$), respectively. Furthermore, no significant effects can be observed for all possible two- and three-way interactions. However, there appears to

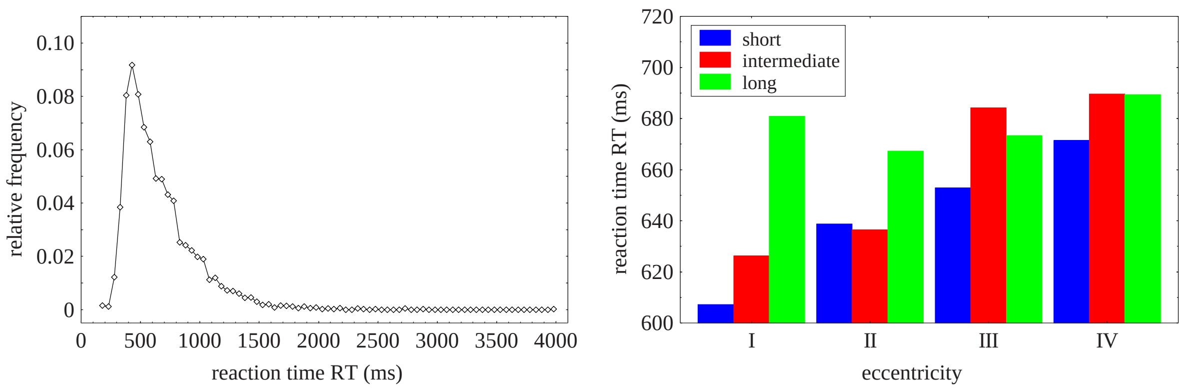


Figure 6.3: Left: Cumulative relative frequency distribution of reaction times RT over all eccentricity regions, line segment lengths and orientation levels. Right: Reaction time RT as a function of eccentricity, separated for short, intermediate and long line segments.

be a tendency towards an interaction between eccentricity and line segment length ($F(6;66) = 2.04; p = 0.072$) which suggests that short and intermediate lines require less processing time for length assessment only when presented at near-foveal locations (Eccentricities I and II). Furthermore, a closer inspection of the data reveals that RT remains at a high level between 667.3 and 689.3 ms for long line segments, independent of the eccentric presentation position of the target line segments. Figure 6.3 (right) illustrates the means of RT as a function of the Eccentricities I–IV and the target line segment lengths (short, intermediate, long).

Length Deviation DL

Similar to the *absolute* (positive) and *directional* value types for the radial, tangential and Euclidean positional deviations in Experiment E0, we also distinguish between these two types here. Whereas the absolute values give a better impression of how much the lengths of the comparison line segments differ from those of the target line segments, the analysis of the directional data is indispensable in determining whether target lengths were under- or overestimated. For the following analyses, we will thus consider the length deviations DL_p, which represents the positive deviations between the lengths of the comparison and the target line segments. DL, the directional pendant, will be negative in case the length of the comparison line segment is shorter than that of the target, and positive otherwise. Both DL and DL_p are *relative* measures that correlate the deviation to the target length. Example: A comparison line segment that is adjusted to LC = 110 pixels when the target is LT = 100 pixels long constitutes

$$DL = (LC - LT)/LT = 0.1, \tag{6.1}$$

i.e. a length deviation of (+)10%.

Positive Relative Length Deviation DL_p

In order to test the effects of the eccentricity region, the target line segment length and orientation on DL_p, a three-way analysis of variance is conducted. Significant main effects can be established for the factors eccentricity ($F(3;33) = 11.82; p < 0.001$) and target line segment length ($F(2;22) = 33.25; p < 0.001$). A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between the following eccentricity levels: ($R_{crit} = 0.038; p = 0.040$) for the comparison of DL_p between the Eccentricities I vs. II, ($R_{crit} = 0.045; p = 0.001$) for I vs. III, ($R_{crit} = 0.049; p < 0.001$) for I vs. IV, ($R_{crit} = 0.041; p = 0.035$) for II vs. III and ($R_{crit} = 0.043; p = 0.002$) for II vs. IV. In contrast, only a tendency towards the existence of a significant difference in DL_p can be found between the Eccentricities III and IV ($R_{crit} = 0.034; p = 0.089$). The differences between all levels of the factor target line segment length are significant (Newman-Keuls post-hoc test) with respect to DL_p: ($R_{crit} = 0.084; p < 0.001$) for the comparison between short and intermediate lengths, ($R_{crit} = 0.080; p < 0.001$) for short vs. long lengths and ($R_{crit} = 0.069; p = 0.042$) for intermediate vs. long lengths.

When data is averaged over lengths and orientations (for all subjects), comparison line segment lengths deviate from the target lengths by 16.6% for Eccentricity I, 18.6% for Eccentricity II, 21.9% for Eccentricity III and 23.8% for Eccentricity IV. A cumulation of data over the factors eccentricity and orientation yields that subjects (incorrectly) adjust the length of the comparison line segment with deviations of 31.8% (short), 17.2% (intermediate) and 11.8% (long) on average. The factor orientation does not yield a significant main effect on DL_p ($F(2; 22) = 0.22; p = 0.800$).

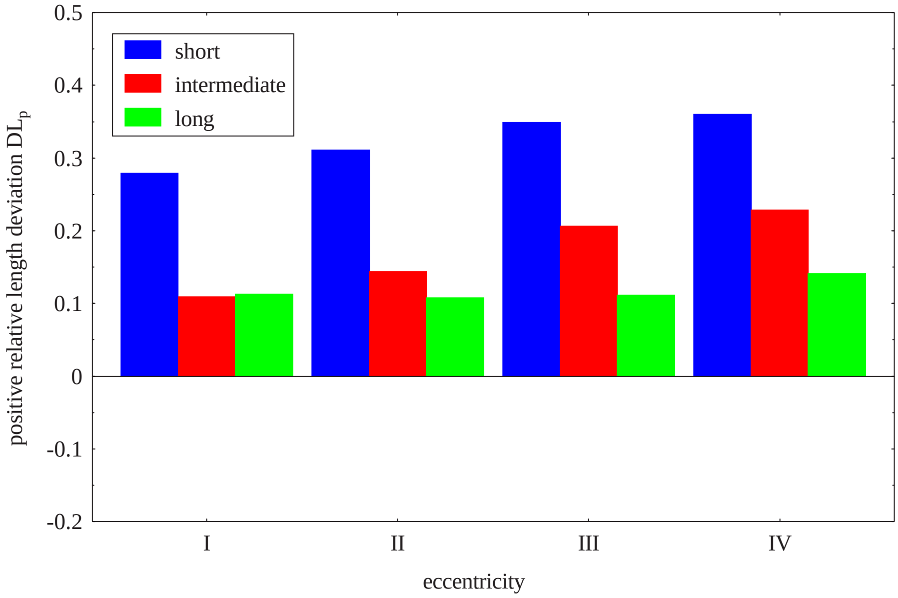


Figure 6.4: Positive relative deviation DL_p of the length of the comparison from the target line segment as a function of Eccentricity I–IV and target line segment length (short, intermediate, long).

In addition, the interaction between eccentricity and target line segment length reaches significance level ($F(6; 66) = 3.87; p = 0.002$). This can be attributed to the fact that DL_p constantly increases with greater eccentricities for short and intermediate line segments, whereas it remains unaffected for long line segments. For short line segments, DL_p is computed to be 0.28, 0.31, 0.35, 0.36, for intermediate length 0.11, 0.14, 0.21., 0.24, and for long line segments 0.11, 0.11, 0.11, 0.14 – each for the respective Eccentricities I–IV. This is supported by a post-hoc comparison of means using a Newman-Keuls test. It reveals significant differences between the four eccentricity levels for targets with short and intermediate lengths. In contrast, such differences cannot be found between the eccentricity levels for long targets[1]. No other interactions show significant effects on DL_p. Figure 6.4 shows the positive relative length deviation DL_p as a function of eccentricity and target line segment length.

[1]Due to the large number of results for the factor combinations of the Newman-Keuls test in the form ($R_{crit} = ...; p = ...$), these individual values are not explicitly reported here.

Relative Length Deviation DL

In order to investigate the directional extent of the line segment length assessment, DL is subjected to an identical multi-factorial analysis of variance as was conducted for DL_p before.

The analysis yields a significant main effect of the factor eccentricity on DL ($F(3;33) = 19.57; p < 0.001$). The target line segment length is generally overestimated, increasingly so with increasingly eccentric presentation. The overestimation effect reaches the following values: 4.8% when the target line segment is presented within the eccentricity region I, 9.6% in eccentricity region II, 15.7% in eccentricity region III and 17.9% in eccentricity region IV. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between the following eccentricity levels: ($R_{crit} = 0.052; p = 0.014$) for the comparison of DL between the Eccentricities I vs. II, ($R_{crit} = 0.059; p < 0.001$) for I vs. III, ($R_{crit} = 0.058; p < 0.001$) for I vs. IV, ($R_{crit} = 0.056; p = 0.004$) for II vs. III and ($R_{crit} = 0.059; p < 0.001$) for II vs. IV. In contrast, no significant difference in DL can be found between the Eccentricities III and IV ($R_{crit} = 0.044; p = 0.120$).

Another significant main effect on DL can be found for target line segment length ($F(2;22) = 60.37; p < 0.001$). If we average over eccentricity and orientation, a mean overestimation of 28.9% for short and of 8.9% for intermediate line lengths emerges. Long line segments are underestimated by 1.9% on average. According to a Newman-Keuls post-hoc test, the differences between all levels of the factor target line segment length are significant with respect to DL: ($R_{crit} = 0.090; p < 0.001$) for the comparison between short and intermediate lengths, ($R_{crit} = 0.092; p < 0.001$) for short vs. long lengths and ($R_{crit} = 0.075; p = 0.006$) for intermediate vs. long lengths.

Again, no significant main effect for the factor orientation can be observed ($F(2;22) = 0.66; p = 0.524$). The further analysis shows that the previously (for DL_p) significant

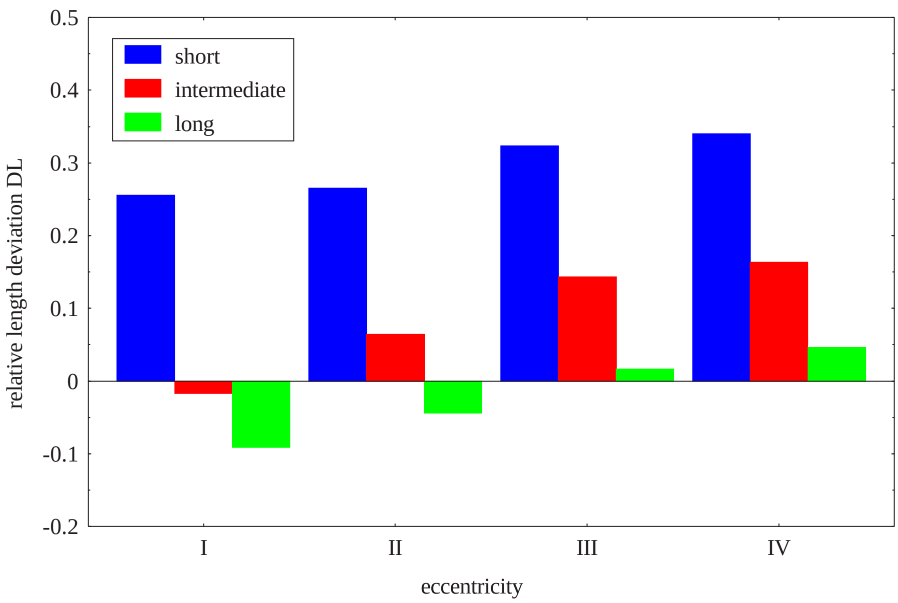


Figure 6.5: Relative deviation DL of the length of the comparison from the target line segment as a function of eccentricity and target line segment length.

interaction between eccentricity and target line segment length prevails for DL ($F(6; 66) = 2.86; p = 0.015$), again confirmed by post-hoc comparisons of means using a Newman-Keuls test. In analogy to Figure 6.4, Figure 6.5 illustrates the relative length deviation DL as a function of eccentricity and target line segment length.

6.3 Discussion and Conclusions

Again, we will briefly summarise the effects that the independent variables exerted on the dependent variables in Experiment E1. The most fundamental observations are that

1. the lengths of the target line segments are generally *overestimated*,
2. the factor eccentricity exerts a significant effect on all dependent variables,
3. the factor target line segment length exerts a significant effect on $DL_{(p)}$, but not on RT and
4. the factor target line segment orientation does *not* exert a significant effect on any dependent variable.

How can these observations be interpreted? In general, none of the effects present a great surprise. However, to find that the target line segment lengths are *overestimated* almost throughout, is rather unexpected at first sight and seems to contradict the results of some earlier investigations (e.g. Newsome, 1972; Schneider, 1978). This also means that some of the previously established and frequently quoted explanations do not apply to the present study and must therefore be reviewed – which will be done later in this section. But first, what do the other observations reveal and to which conclusions regarding the peripheral perception of line segment lengths do they lead?

As the same gaze-contingent viewing conditions apply here as in the location assessment task of Experiment E0, subjects consequently encounter the same difficulties associated with the obligation to constantly observe a stationary fixation point. We could thus not expect to find fixation or reaction times (RT) within a completely different magnitude scale. The experimental data entirely confirms this hypothesis, as an inter-experimental comparison shows no significant effect for the factor “experiment” ($F(1; 25) = 0.001; p = 0.991$). When RT is considered an indicator for the difficulty of the assessment task, it appears that subjects do not find it more difficult to assess a line segment length than a marker location. In both tasks, the reaction time is almost identical, with a mean RT of approximately 660 ms. These relatively short reaction times demonstrate the difficulty induced by the gaze-contingent experimental task. Results hint that maintaining a stable fixation for much longer than the typical, “natural” fixation period is hardly ever achieved or possibly presents too great a challenge to accomplish for subjects.

But, as results from Experiment E0 suggested already, RT is not an ”all-independent” variable. Within the overall “RT-frame” that restricts reaction times to relatively low values due to the gaze-contingent task, the factor eccentricity, for example, exerts a significant influence on reaction times. The assessment of the lengths of the target line segments becomes more and more difficult with increasing distance from the fixation point. Again, subjects obviously try to compensate for the increased assessment difficulty by prolonged reaction times in this Experiment E1. However, the following analyses of the assessment "quality", i.e. the length deviation $DL_{(p)}$ of the comparison line segment from the target line segment, rather questions the success of the "RT-compensation-strategy": $DL_{(p)}$ increases for more peripheral line segment presentations, i.e. the length assessment quality deteriorates. As in Experiment E0, this might again be attributed to the required *"mental translation"*: Longer mental translation distances require more time, explaining the increase of RT when the lengths of line segments have to be assessed in more peripheral regions.

Before we turn to the discussion of the length deviation results, two more points have to be made with respect to the analysis of RT. First, the values of RT now show a pronounced difference between the eccentricity regions II and III. In contrast to the almost identical values measured in Experiment E0 for these two eccentricity regions, the observations here no longer suggest the existence of three designated eccentricity levels, but rather a continuous eccentricity band without clearly identifiable boundaries.

Second, the interaction effects of eccentricity and target line segment length on RT, although only tendential, encourage some speculation. We observed that RT yields relatively high values for long line segments – compared to RT measured for short and intermediate lengths – with only little divergence between the eccentricity levels I–IV. This can be understood when recalling that the long line segments were chosen such that their lengths represent a "peripheral length" (due to the extent of the foveal eccentricity region I, line segments with a peripheral length could only be 7^o long here (see Section 4.1)). Subjects obviously find the assessment of such length particularly difficult, even when the line segments are presented in proximity to the fixation point, and take more time to accomplish this task. In summary, it could thus be that not only a far eccentric location of the stimulus, but also a line segment length that cannot be perceived foveally results in prolonged processing times. Furthermore, the relative stability of RT over the different eccentricities for assessing long line segments, i.e. the independence of RT from the eccentricity region, could indicate that, in this case, the (long) reaction times can mainly be attributed to the *processing difficulties induced by peripheral length rather than by eccentricity*.

One of the most striking findings of all the studies presented in this thesis is that the lengths of the target line segments are generally *overestimated*. Although a number of recent studies arrive at similar results (see Section 2.2, e.g. Nakatani, 1995; Tsal & Shalev, 1996; Prinzmetal & Wilson, 1998; Tsal, 1999), the majority of earlier investigations observed *underestimation* effects during size or length assessment in peripheral regions (see Section 2.2, e.g. Pearce & Taylor, 1962; Richards & Miller, 1971; Newsome, 1972; Schneider, 1978; Thompson & Fowler, 1980). In Experiment E1, short and intermediate line segments are overestimated in all but the foveal eccentricity region. Here, the assessment for intermediate line segments is highly accurate and shows a deviation of only -2%, i.e. a slight underestimation of the target line segment length. Such highly accurate assessment levels can also be found for long line segments, independent of the eccentricity region. The analysis of the "directional" length deviation DL in particular reveals that long line segments lengths are no less than 9% under- and no more than 5% overestimated. This is significantly more accurate than is the case with the other two line segment lengths. Furthermore, these highly accurate assessments of long line segments can be maintained even in the more eccentric regions. A possible explanation for these observations could be the more salient image the longer segments yield on the retina, due to the excitation of more receptors as in the case of shorter line segments. Whereas for those, in particular for the short length in more peripheral eccentricity regions, only a "blotch" with possibly no directional or length information might be perceived, the orientation and extent of longer line segments should still be visible, but blurred as well. For intermediate line segment lengths, a reasonable amount of length information seems to be available if not presented too far from the fixation point. For far peripheral locations then, the line segment shape becomes increasingly blurred and so does the length information, leading to greater uncertainty in the perceived size and thus less accurate assessments.

The fact that all assessments are independent of the orientation of the target line segment could be expected. As the comparison line segments were presented in the same orientations as the respective targets, possible interference from horizontal-vertical effects could be eliminated. These could have been expected if the comparison marker was presented in a fixed, for example always horizontal orientation: Due to the horizontal-vertical illusion (see Section 2.2), the lengths of vertical target line segments should then have been overestimated. However, even with this factor being eliminated, it could have been that orientation affected the length assessment: When, for example, a vertical line segment has to be assessed that is located along the horizontal meridian, i.e. left or right of the fixation point, both its end points have more or less the same distance from the fixation point. When a horizontal line segment is now shown at the same meridial position, its end points have different distances from the fixation point, which might then complicate the length assessment. However, as the findings show, this is not the case. At least when, as in Experiment E1, the line segments lie entirely within one eccentricity region, the factor orientation does not affect the assessment of line segment lengths.

As already mentioned, the *overestimation* effect for most line segment lengths and the fact that this effect is more pronounced with increasing eccentricity could not always be observed in earlier experiments. With only few similar experimental findings, explanations for the causes of such overestimation effects are also sparse. Furthermore, the respective explanatory approaches put forward could only partially account for the experimental observations. They frequently failed to yield a detailed representation of how particular factors influence peripheral length assessment. Even the promising studies of Tsal (1999), Tsal and Bareket (1999) and Tsal and Bareket (2001) and their subsequently introduced concept of "attentional receptive fields" (ARFs), for example, can be considered an appropriate concept only for distinguishing between coarse unattended and fine attended perception (see Section 2.2). It is not clear in how far this concept is able to correctly account for the quantitative aspects of the assessments, i.e. to correctly represent the ratios between the target and comparison dimensions, and how ARFs deal with complementary stimulus attributes, such as line segment orientation. However, it appears to be reasonable to share their view that there exists a significant effect of attention on peripheral stimulus assessment (see earlier studies by Butler (1980), Egyl and Homa (1984) and Müller and Rabbit (1989)), and that it is not a completely preattentive operation (e.g. Sagi & Julesz, 1985).

The *possible explanation* proposed here for the overestimation effects reported in Experiment E1 is based mainly on *two assumptions*: First, we suggest that the line segment's *end points* play an important role for the length assessment. Second, we assume that, for the peripheral length assessment, *similar principles* apply as in the peripheral location assessment task in Experiment E0. In detail, the explanation of the overestimation of line segment lengths in Experiment E1 is based on the finding of Experiment E0 that the actual position of the target marker is perceived as being *shifted towards* the fixation point (underestimation of the *radial* target marker position, see Sections 5.2.1 and 5.3). In contrast, very *little divergence* between the *tangential* position of the comparison and the target marker were noticed. Let us now transfer these observations to the current study, assuming that the principles of location assessment apply to the peripheral perception of line segment lengths as well. It then emerges that, when memorising a peripherally perceived line segment, subjects lay off a *mental representation* (or *mental model* (Johnson-Laird, 1983)) of a line segment of approximately the original (target) length, but shifted towards the fixation point. This (mental) “shift” or *dislocation* of the line segment towards the observer leads to an elongation of the line segment when its mental model is recalled in the reconstruction phase of the experiment, i.e. when the length of the comparison line segment has to be adjusted. This might be due to the *principle of size/length constancy* which states that the size/length of objects seems to increase when they are moved towards the observer (cf. Section 2.2).

Although this approach intuitively appears plausible and well suitable for explaining the overestimation of line segment lengths, further support should be provided that the explanation holds and is based on sensible assumptions. The development of an according (computational) model appears to be promising in that respect. Such a model would enables us to test if and how the perceived length of peripherally presented line segments can be concluded as a result of the peripheral assessment of the location of its end points – as formulated in the (stimulus) *decomposition* hypothesis. This would then allow us to perform a quantitative analysis of the model data and compare the outcome with the empirical findings. In case of a positive correlation of these two data sets, not only support would have been presented for the correctness of the previous assumptions. The model would also suggest a possible explanatory approach that accounts for the major empirical observations. Finally, a model would have been implemented that adequately simulates the quantitative ratios of the assessment effects as well.

However, it would be desirable to develop a model that does not only account for the eccentricity effects on the assessment of line segment *lengths*. Although no significant effect of the factor *orientation* on the length assessment could be established in Experiment E1 – due to the specific experimental procedure – we consider this dimension another essential factor in the characterisation of line segments. Thus, Experiment E2 will be conducted in order to investigate how accurately subjects can assess the orientation of line segments that are again presented at different eccentric locations (Chapter 7). Subsequently, we should be able to discuss the development of a model under the premises that it ideally incorporates both line segment length and orientation assessment (Chapter 8).

Chapter 7

Experiment E2: Orientation Assessment in Peripheral Vision

The last experiment in this series of three experiments investigates the perception of line segments orientation. The “reference” data obtained here allows for the testing of the existence of correlations between the assessment error of peripherally perceived orientations of line segments and the mislocation of marker positions. In analogy to Experiment E1, if a correspondence can be found, this would indicate that observations in this experiment can possibly be attributed to mechanisms that were identified to influence location assessment. The peripheral assessment of line segment orientation might thus be accordingly *decomposed* and could be accomplished by peripherally assessing the locations of the end points of the line segment. The relative position of the end points to each other then yields the line segment orientation.

The following sections describe the experimental method for Experiment E2, based on the methodological preliminaries that were established in Chapters 3 and 4. Subsequently, the results will be presented and discussed which allows us to draw conclusions about the mechanisms that may govern peripheral orientation perception.

7.1 Method

7.1.1 Subjects

The subjects were twelve experimentally naive students – five male and seven female – from the University of Bielefeld. Their average age was 26.1 years. All subjects had normal or corrected-to-normal vision and no pupil anomalies. The subjects were paid for their participation in the experiment.

7.1.2 Stimuli

The stimuli were almost the same as in Experiment E1, differing only in the comparison line segment used.

7.1.3 Apparatus

The apparatus used was the same as in Experiments E0 and E1.

7.1.4 Procedure

The procedural steps in this experiment were almost identical to those in Experiment E1. Only the experimental task varied, subject were asked to assess the *orientation of the target line segment* presented in one of the eccentricity regions I-IV without foveally looking at it. Again, the gaze was restricted to a region of 1^o around the central fixation point (Frame 1) and this contingency was monitored by the eye tracker. When subjects had successfully finished the assessment task and memorised the perceived orientation of the target line segment, they pressed the left button of the computer mouse (Frame 2). Subsequently, a blank screen was shown for 500 ms (Frame 3) and the fixation point reappeared at the center of the display (Frame 4) for 300 ms.

The fixation point was replaced by the comparison line segment (Frame 5) with the line segment center located at the center of the screen. The comparison line segment had the same dimensions as the previously shown target line segment with respect to thickness, colour and length. However, this time the comparison line segment was randomly oriented between 0.0^o and 179.9^o. The subject was instructed to adjust the orientation of the comparison line segment with the computer mouse so that it exactly matched the memorised perceived orientation of the target line segment (Frame 6). Moving the mouse to the left resulted in a counter-clockwise rotation of the comparison line segment around

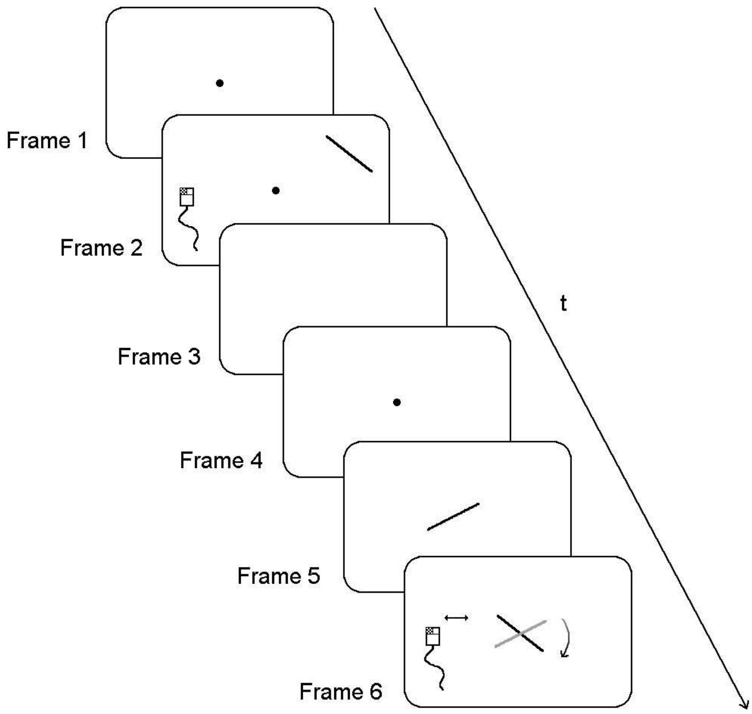


Figure 7.1: The sequence of procedural steps for a trial of Experiment E2. Frame 1: Fixation point. Frame 2: Target line segment orientation assessment. Frame 3: Blank screen. Frame 4: Fixation point. Frame 5: Comparison line segment. Frame 6: Adjustment of comparison line segment orientation.

its center, moving the mouse to the right in a clockwise rotation. A press of the left mouse button confirmed the orientation adjustment and started the next trial. During this adjustment phase, subjects could move their gaze freely across the whole screen. Figure 7.1 illustrates the sequence of procedural steps for one trial.

Subjects viewed a total of 360 stimulus pictures during the experiment, so that each possible combination of the four position eccentricities, the three orientations and the three lengths (see Section 6.1.2) was displayed ten times. Ten practice trials were conducted prior to the experimental trials.

7.2 Results

As the choice of stimuli and the procedural design remains almost unchanged from Experiment E1, no major changes regarding the data analyses are required either. Again, data will be subjected to a three-factorial analysis of variance in order to account for the three independent variables eccentricity region, target line segment length and orientation. The effects of these factors are tested on the dependent variables reaction time RT and, here, on the orientation deviation DO of the target line segment from the comparison line segment.

7.2.1 Dependent Variables

Reaction Time RT

First, we chart the relative frequencies of the reaction time RT in a histogram (see Figure 7.2, left). The distribution is again based on all measured values for RT, irrespective of eccentricity, target line segment length or orientation, and takes into account the data from all subjects. A minimum RT of 154 ms and a maximum RT of 4310 ms are measured, the overall mean is 662 ms. The histogram reaches a peak at approximately 410 ms. Approximately 95% of the values lie within the interval of 250 to 1650 ms, the general shape of the distribution for RT closely resembles those of Experiment E0 and Experiment E1 and can be fitted by an asymmetrical function with positive skewness of +2.10.

The analysis of variance yields a significant main effect on RT for the factor eccentricity ($F(3;33) = 10.02; p < 0.001$). When the target line segment is presented foveally (Eccentricity I), subjects on average require 621.2 ms to assess its orientation, for more eccentric presentation positions, RT increases from 646.7 ms (Eccentricity II) and 660.7 ms (Eccentricity III) to 722.0 ms (Eccentricity IV) for the orientation assessment. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between the following eccentricity levels: ($R_{crit} = 46.011; p = 0.031$) for the comparison of RT between the Eccentricities I and III, ($R_{crit} = 48.891; p < 0.001$) for I vs. IV, ($R_{crit} = 47.775; p = 0.001$) for II vs. IV and ($R_{crit} = 46.990; p = 0.002$) for III vs. IV. In contrast, only a tendency towards the existence of a significant difference in RT can be found between the Eccentricities I and II ($R_{crit} = 42.009; p = 0.086$). No significant difference exists between the Eccentricities II and III ($R_{crit} = 38.655; p = 0.211$).

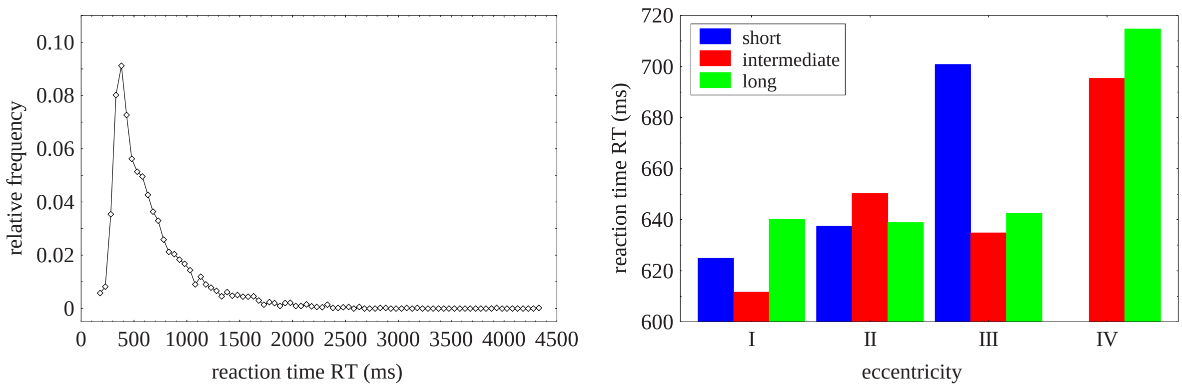


Figure 7.2: Left: Cumulative relative frequency distribution of reaction times RT over all eccentricity regions, line segment lengths and orientation levels. Right: Reaction time RT as a function of eccentricity, separated for short, intermediate and long line segments.

Furthermore, the factor target line segment length exerts a significant effect on RT ($F(2;22) = 5.10; p = 0.015$). On average, subjects take longer to assess the orientation of the target line segments when they are short (682.3 ms) than when they are intermediate (650.2 ms) or long (655.3 ms) in length. According to a Newman-Keuls post-hoc test the differences between the following levels of the factor target line segment length are significant with respect to RT: ($R_{crit} = 27.119; p = 0.013$) for the comparison between short and intermediate lengths and ($R_{crit} = 26.001; p = 0.044$) for short vs. long lengths. RTs for intermediate vs. long lengths do not significantly differ ($R_{crit} = 21.340; p = 0.101$), only a slight tendency can be noted.

A closer inspection of the data (see Figure 7.2, right) reveals that RT most drastically increases with increasing eccentricities for short lengths whereas for intermediate and, in particular, for long target line segments such a considerable increase of RT can only be observed for Eccentricity IV. However, the interaction between eccentricity and target line segment length does not exert a significant effect on RT ($F(6;66) = 1.69; p < 0.136$).

The factor orientation, does not reach significance either, but demonstrates a tendency ($F(2;22) = 2.88; p < 0.077$) towards shorter RT for target line segments that are oriented (near-)vertically (639.9 ms), compared to RT for (near-)horizontal (672.7 ms) and (near-)oblique oriented (675.4 ms) target line segments. No interaction exerts a significant effect on RT. Figure 7.2 (right) shows RT as a function of eccentricity and target line segment length.

Orientation Deviation DO

Rather than making distinctions between analyses for absolute or directional and relative values as in the previous experiments, there is no need for separate investigations regarding the orientation deviation DO. As there appears to be no reason to assume a directional effect (systematic clock- or counter-clockwise DO) of the rotation of the comparison line segment relative to the target orientation, all values for DO are positive. We will enter the absolute positive measured values of the orientation difference (in degrees) between the target and the comparison line segments in a three-factorial analysis of variance to test the effects of the independent variables eccentricity, target line segment length and orientation on DO.

The analysis of variance yields significant main effects for all factors. First, the effect of eccentricity on the orientation deviation DO reaches significance ($F(3; 33) = 11.75; p < 0.001$). As for most other eccentricity effects before, the subjects' performance deteriorates the further away the target line segment appears from the fixation point. On average, the subjects in Experiment E2 misjudge the orientation of the target line segment by 6.0 degrees in Eccentricity I, by 6.4 degrees in Eccentricity II, by 7.1 degrees in Eccentricity III and by 7.5 degrees in Eccentricity IV. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences exist between all eccentricity levels: ($R_{crit} = 0.540; p = 0.048$) for the comparison of DO between the Eccentricities I and II, ($R_{crit} = 0.695; p = 0.001$) for I vs. III, ($R_{crit} = 0.731; p < 0.001$) for I vs. IV, ($R_{crit} = 0.655; p = 0.028$) for II vs. III, ($R_{crit} = 0.685; p = 0.002$) for II vs. IV and ($R_{crit} = 0.544; p = 0.049$) for III vs. IV.

Next, the factor target line length is also found to have a highly significant effect on DO. The respective analysis yields a significance level of ($F(2; 22) = 31.67; p < 0.001$), manifested in a greater mean orientation deviation for short line segments (7.4 degrees) than for intermediate ones (6.9 degrees), and in a yet smaller DO for long line segments (5.8 degrees). According to a Newman-Keuls post-hoc test the differences between all levels of the factor target line segment length are significant with respect to DO: ($R_{crit} = 0.448; p = 0.038$) for the comparison between short and intermediate lengths, ($R_{crit} = 0.555; p < 0.001$) for short vs. long lengths and ($R_{crit} = 0.547; p < 0.001$) for intermediate vs. long lengths. Figure 7.3 shows DO as a function of the eccentricity region (I–IV) and the length of the target line segments (short, intermediate, long).

Finally, the third factor, target line orientation, also shows a significant effect on DO

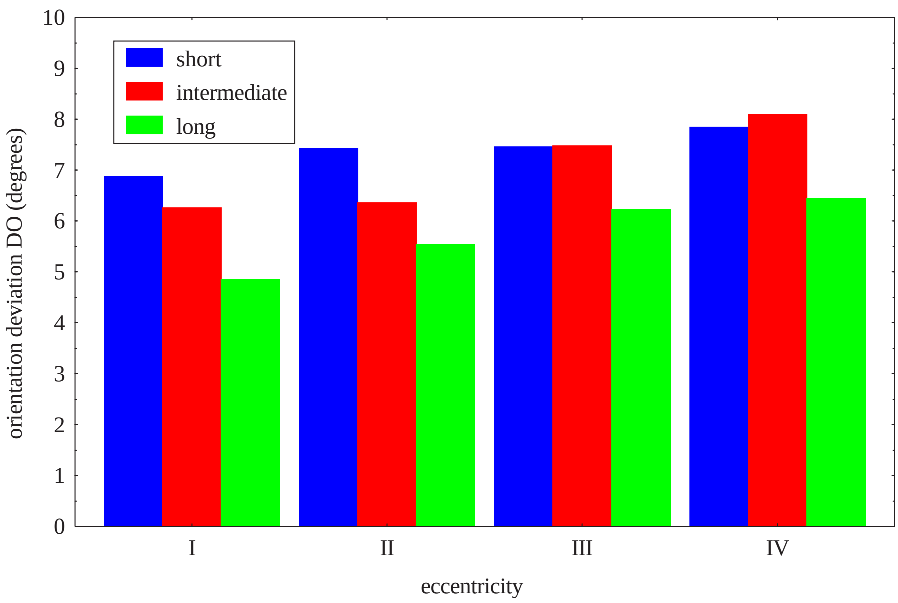


Figure 7.3: Orientation deviation DO of the comparison from the target line segment as a function of Eccentricity I–IV and target line segment length.

($F(2;22) = 9.34; p = 0.001$). When target line segments are oriented near-horizontally (i.e., according to our definition of the horizontal category, $0^o \pm 22.5^o$ (see Section 4.1)), the average orientation deviation measures 5.4 degrees. DO then increases for oblique orientations ($45^o \pm 22.5^o$ or $135^o \pm 22.5^o$) to 7.3 degrees and further to 7.7 degrees for vertical line segments ($90^o \pm 22.5^o$). According to a Newman-Keuls post-hoc test the differences between the following levels of the factor target line segment orientation are significant with respect to DO: ($R_{crit} = 1.345; p = 0.003$) for the comparison between horizontal and oblique orientations and ($R_{crit} = 1.387; p = 0.002$) for horizontal vs. vertical orientations. No significant difference in DO can be found for the comparison between oblique and vertical orientation levels ($R_{crit} = 1.136; p = 0.334$). Figure 7.4 shows DO for all eccentricity regions (I–IV), separated for the three possible orientations of the target line segments (horizontal, oblique, vertical).

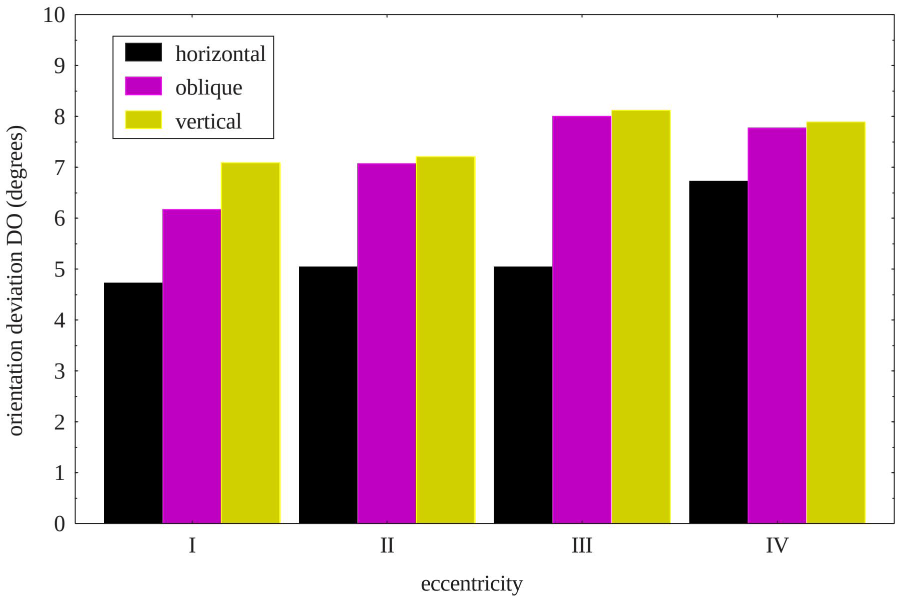


Figure 7.4: Orientation deviation DO of the comparison from the target line segment as a function of Eccentricity I–IV and target line segment orientation.

The only interaction that reaches the significance level is that between target line segment length and orientation ($F(4;44) = 3.28; p = 0.019$). For horizontal target line segments, irrespective of the target line segment length and aggregated over all eccentricities, the orientation deviation DO remains approximately constant at a low level (5.4 degrees). A post-hoc comparison of means using the Newman-Keuls test reveals that no significant differences exist between the three length levels when the target is oriented horizontally: ($R_{crit} = 0.834; p = 0.361$) for short vs. intermediate lengths, ($R_{crit} = 0.867; p = 0.295$) for short vs. long lengths and ($R_{crit} = 1.023; p = 0.129$) for intermediate vs. long lengths. In contrast, when oriented either obliquely or vertically, DO almost linearly decreases from 8.4 degrees for short to 7.8 degrees for intermediate and to 6.2 degrees for long target line segments. Accordingly, a Newman-Keuls test reveals significant differences between the three length levels. Oblique targets: ($R_{crit} = 1.189; p = 0.045$) for short vs. intermediate lengths, ($R_{crit} = 1.332; p < 0.001$) for short vs. long lengths and ($R_{crit} = 1.237; p = 0.006$) for intermediate vs. long lengths. Vertical targets: ($R_{crit} = 1.003; p = 0.041$) for short vs. intermediate lengths, ($R_{crit} = 1.310; p < 0.001$) for short vs. long lengths and ($R_{crit} = 1.302; p = 0.001$) for intermediate vs. long lengths.

All other two-way interactions and the three-way interaction between eccentricity, target line segment length and orientation do not show significant effects on the orientation deviation DO.

7.3 Discussion and Conclusions

As before, we will again briefly summarise the main results of the current experiment. The most fundamental observations the analyses yield are as follows:

1. The factor eccentricity exerts a significant effect on RT and DO.
2. The factor target line segment length also exerts a significant effect on RT and DO.
3. The factor target line segment orientation exerts a significant effect on DO, but only a tendential effect on RT.

As far as the reaction time RT is concerned, the results of this "orientation experiment" closely resemble those of the previous Experiments E0 and E1. The similarity holds with respect to both the quantitative statistical values, for example the mean RT, and the more qualitative results, such as the relative frequency distribution of RT. In an inter-experimental comparison, a two-way analysis of variance of the factors experiment and eccentricity – the only two that could be compared between the Experiments E0, E1 and E2 – does not reveal any significant difference concerning the effect of "experiment" on RT. The reaction times measured in Experiment E2 neither differ significantly from those in Experiment E0 ($F(1; 25) = 0.001; p = 0.988$) nor from those in Experiment E1 ($F(1; 22) = 0.001; p = 0.981$). It appears that subjects do not find it more difficult to assess a line segment orientation than to assess its length or a marker location. This, of course, again assumes that RT can be considered a valid indicator for task complexity even under the gaze contingent viewing conditions that apply in Experiment E2 as well.

The fact that the factor eccentricity exerts a significant effect on RT seems to supports this assumption: With increasingly eccentric location of the target line segment – and thus a certainly more complex orientation assessment task – RT increases in Experiment E2. The orientation assessment appears to be a particularly difficult task in eccentricity region IV. In analogy to Experiments E0 and E1, this could again be attributed to the *"mental translations"* which may take longer when covering longer distances – as the case when orientations of line segments are assessed in more peripheral regions. When the data is accumulated over line segments length and orientation, the difference in RT between the eccentricity regions II and III is by far smaller than for the comparison between the other eccentricity regions. This could be understood as at least a further *hint of the existence of three designated eccentricity regions*, just as found for RT in Experiment E0. Within these eccentricity regions, RT shows very little variation. Significant changes occur only in the "border regions". It must be remembered, however, that the analyses of Experiment E1 did not support this hypothesis.

Apart from the eccentric region, RT is significantly influenced by the length of the target line segment in this experiment. In Experiment E1, the length of the target line segments had no such effect on RT, but it subsequently emerged that the length of short(er) line segments could be less accurately assessed. If we conclude that these lengths must thus have been more difficult to judge, the lack of a corresponding effect on RT, i.e. longer RT for short(er) line segments, suggests that subjects did apparently not attempt to compensate for the increased complexity of assessing short line segment lengths in Experiment E1 through an increase in RT. This, however, is the case in Experiment E2. The orientation assessment of short line segments appears to be a far more complex task than that of intermediate or long line segments, in particular in the far peripheral regions. Subjects try to compensate for the higher orientation assessment complexity of short line segments through the increase in RT. In the gaze-contingent stimulus presentation condition this is done again within the limited (time) range of still acceptable concentration effort.

The subjects' tendency – only marginally short of significance – to produce shorter reaction times when the target line segments are displayed in (near-) horizontal rather than in (near-) oblique or (near-) vertical orientations hints at a preference of horizontal over vertical information processing strategies. Indeed, the tendency towards the facilitatory effects of processing horizontal line segments as visible in RT is supported by the significant effect that target line orientation exerts on the orientation deviation DO. The fact that the orientation of horizontal line segments can be more accurately assessed than those of oblique and vertical line segments clearly *favours horizontal processing*. This is possibly due to the anatomy/physiology of the eye and the retina and, probably even more so, to the fact that most visual information processing requires a horizontally oriented strategy, such as reading – at least in Western cultures. These requirements are supposed to have influenced preferred visual strategies in many other tasks as well and thus, as a habituation effect, resulted in the *improved "visual performance" along this orientation*. In eye-tracking studies at the University of Bielefeld this was shown, for example, in comparative visual search (e.g. Pomplun, 1998) and numerosity estimation tasks (Koesling, 1997; Koesling et al (submitted)).

Although it takes subjects longer to assess the orientation of the target line segments in more peripheral regions, the extra time does not help to improve the assessment accuracy in general. In some cases, however, there appears to be such a facilitatory effect; for example for short line segments: While RT is about equal for short and intermediate line segments in the eccentricity regions I and II, the orientation deviation DO is significantly larger for short line segments. However, with the sharp increase of RT for short line segments that are presented in the eccentricity regions III and IV, no such difference in DO between short and intermediate lengths is visible in the eccentricity regions III and IV any more. These observations might indeed suggest that for specific lengths an increased reaction time helps to more accurately assess line segment orientation. Nevertheless, subjects do not succeed in achieving the same assessment accuracy level for short (and intermediate) length as for long line segments. The accuracy differences regarding the orientation assessment between these two types of line segment length, i.e. short(er) and long, remain about the same, independent of the eccentricity region and unaffected by RT differences.

As before, the decreasing accuracy of the orientation assessments must probably be attributed to a more and more "blotch"-like retinal image the further away the target stimulus is displayed from the fixation point. Such a blurred representation is then laid off as an equally blurred mental image or model. This obviously renders the accurate assessment of line segment lengths difficult as the end points of line segments and thus the line segment's extent cannot exactly be determined (see Experiment E1, Chapter 6). Furthermore, the orientation of a line segment can only vaguely be assessed when only a rather diffuse image of the stimulus is perceived in the periphery. It could even be expected that, at some stage, either in very far eccentric locations or for very short line segments, all directional information is lost. The only information available to the visual system then would be the existence of some object in the periphery, but none of its features such as its orientation and length relevant here.

Let us now – at least partly – consider again the suggestions made at the end of the previous chapter. It was proposed that the end points of a line segment play an important role for its length assessment (Experiment E1) and that their mislocation (Experiment E0) towards the observer leads to the overestimation of line length. With regard to the assessment of the orientation of line segments, possibly similar processing principles apply.

Indeed, it appears to be a promising approach to think of orientation assessment as a process determined by the perceived locations of the line segments' end points as well. In detail, the computation of the relative spatial positions of the two end points to each other should yield the target orientation information. This could be laid off as a mental representation and subsequently be recalled during the adjustment of the orientation of the comparison line segment. If we take into account the findings for the location assessment from Experiment E0, in particular considering the eccentricity effects on the location accuracy along the radial and tangential axes, these could also be reflected in and probably account for some of the results of Experiment E2. For example, due to the greater variance along the radial rather than along the tangential axis in the location assessment task of Experiment E0, a considerable variation in the orientation assessment must be expected – and could indeed be observed in Experiment E2. The same is true for the increased uncertainty in the orientation assessment in more eccentric regions, which appears plausible when we take into account the increasing location uncertainty – mainly in the radial direction – with increasing eccentricity in Experiment E0. Thus, this approach again seems plausible and intuitively suggests to account for the orientation deviations observed in Experiment E2. However, if it really does, this must be validated.

Due to the close resemblance of the suggested explanatory approaches for the peripheral assessment of the length and orientation of line segments, it now appears to be favourable to develop a *common model*. This should enable us to test if and how *both the perceived length and orientation* of peripherally viewed line segments can be concluded as a result of the peripheral *assessment of the location of its end points*. As suggested in the previous chapter, an appropriate model should not only present support for the adequacy of the assumptions made – the *decomposition hypothesis* – and suggest an explanatory approach that may account for the empirical observations. Furthermore, it should adequately simulate the quantitative ratios of the assessment effects as well. The attempts made to design, implement and validate such a model are presented in the following chapter.

Chapter 8

Modelling Eccentricity Effects

8.1 Why Modelling?

A close inspection of the psychological literature reveals that, in general, the majority of studies follows the same strategy to arrive at its conclusions. After the motivation of a study, the review of related works and the choice of the experimental conditions and setup, the actual experiment is conducted. Next, the collected empirical data is subjected to qualitative and quantitative, mainly statistical analyses. Characteristic values such as means or standard deviations are computed and statistical analyses are performed in order to relate the experimental observations – the dependent variables – to the systematically varied parameters – the independent variables (e.g. Sichelschmidt & Carbone, 2003).

All these steps are rather straightforward and present a more or less standardised procedure. The exciting, but often troublesome part of work only starts here. The crucial questions that scientific studies should attempt to find an appropriate answer for are: Why did we get the results just as they are, what do the observations tell us and how can the findings be interpreted in the experimental and, preferably, in a more general context? One of the common problems of the discussions of experimental results is that conclusions drawn from the empirical data are not entirely conclusive. Many conclusions apparently rely on vague interpretations of the observations and sometimes incorporate a considerable amount of speculation.

In an attempt to *provide more support* their interpretations and conclusions, some authors propose *models*, formalised descriptions of their reasoning on the basis of assumptions the experimental data seem to suggest. Unfortunately, most of these models only unspecifically describe the (proposed) theory and rarely contain clear suggestions with respect to a concrete implementation of the model. Very few authors present models that can be *parameterised* so that an *algorithmic implementation* realises the reproduction of empirical data. However, only such a *simulation* enables us to compare empirical and simulation data in order to test the correctness of the model. In return, this then allows for testing the validity of the initial premises and the suggested interpretation of the empirical data that led to the generation of the model. This closed loop of empirical data acquisition — interpretation — modelling — verification represents a promising strategy for making reliable statements on the processes underlying specific (human) performance. Exactly these are the premises for the development of the present model.

8.2 A Model for Peripheral Visual Perception of Line Segments

The aim now is to develop a specific model to simulate the processes involved in the peripheral visual perception of the length and the orientation of line segments. The model will be implemented as an algorithm and produce data in analogy to that generated by subjects in the experimental studies of the Experiments E0, E1 and E2. This then allows for the direct comparison of the empirical and simulated data sets in order to validate the correctness of the model. In case of a positive correlation, it can be concluded that the model might indeed account for the underlying perception principles. This means that we have possibly identified the correct processing strategy pursued by the subjects. If there is no positive correlation, at least an adequate strategy to solve these assessment tasks has been successfully implemented.

The following sections will motivate the model idea, determine the modelling preliminaries and explain the methods in detail. The implementation of the model is described and finally the simulation results are presented and discussed with respect to the empirical findings of Experiments E1 and E2.

8.2.1 Model Motivation and Concept

The underlying ideas for the modelling approach pursued here were already briefly introduced in the previous chapters. We will now present these ideas in detail and lay out the procedural structure of the model.

The proposed model approach for the peripheral assessment of line segments is based on the *decomposition hypothesis* (see Section 2.4) and assumes that *end point information* is essential for the assessment of line segment attributes such as *length* and *orientation*. This modelling idea is inspired by results of earlier studies (see Section 2.3, e.g. Buchsbaum, 1972; Ikeda et al., 1977). Subjects' comparison acuity was found to deteriorate drastically in experiments that only displayed line segment fragments or obliterated the terminal sections so that the whole line segment was not visible at any one time. The new conclusions from the findings of Experiments E0, E1 and E2 could now suggest that not only end point information is important for line segment assessment, but that there might exist a direct correlation between the accuracy in line segment assessment and the accuracy in positional assessment. It should in fact be possible to directly infer line segment length or orientation accuracy from position assessment accuracy, i.e. to compute the quantitative values of the *length and orientation divergences* based on those values of the *positional divergences*. If this assumption proves to be correct, it could be further concluded that the *geometrical structure* of objects may guide the perceptual and cognitive processes that determine the assessment of geometrical object attributes – at least as far as the assessment of line segment length and orientation is concerned.

In detail, the *line segment length and orientation assessment* will be modelled as the *assessment of two positional markers* in an eccentricity region. Each marker position can only be assessed – as Experiment E0 demonstrated – with a specific uncertainty in its radial and tangential position. If, subsequently, the *difference between the two position assessments*, i.e. their *distance*, is computed, this should yield a similar result as the assessment of the *length of a line segment* (Experiment E1) in the same eccentricity region and determined by end points that coincide with the two previously shown markers. Of course, the same should be true if we compare the spatial relation between the two position assessments, yielding an orientation, with the assessment of the orientation of a line segment such as shown in Experiment E2.

Although based on obviously sensible assumptions, this model must now be tested for its correctness and capability to reproduce the empirical data. Only then can we assume that it supports the correctness of the assumptions, suggests an appropriate explanation that may account for (some of) the empirical observations and adequately simulates the quantitative ratios of the assessment effects. How can the model now be implemented to yield the desired support?

8.2.2 Model Implementation

So far, the presentation of the model concept only gave a rather theoretical account of its realisation. We will now discuss the computational steps it requires to implement the modelling approach in an algorithmic form. Specifically, we suggest the following procedure to accomplish the implementation of the proposed model:

(a) Description of the distribution of the position assessments for the target marker, based on the empirical data and the statistical analyses of Experiment E0.

(b) Generation of a first position coordinate that takes into account (a).

(c) Analogous generation of a second position coordinate so that the spatial relations of the underlying target marker positions reflect the lengths and orientations of the target line segments of Experiments E1 and E2, respectively.

(d) Computation of the distance between and the spatial relation of the two coordinates (the end points of a "virtual" line segment), yielding simulated length and orientation information, respectively.

(e) Statistical analysis of the simulation data in analogy to the previous analyses of the empirical data.

(f) Comparison of the simulation and the empirical data sets for model validation.

In accordance with the list of procedural steps, we will first address the task of finding a suitable description for the distribution of the positional assessments for the target marker. As the analyses of the empirical data recorded in Experiment E0 revealed, the position of the target marker could only be reproduced with a specific uncertainty. Subjects were unable to exactly match the comparison marker position with that of the previously shown target marker they had peripherally perceived and memorised. This positional mismatch was manifested in the marked positional deviations of the comparison from the target marker positions, mainly dependent on the eccentricity region where the target marker was displayed. Furthermore, the extent of the positional mismatch differed significantly between the radial and the tangential direction. For a given target marker position, a (sample) distribution of comparison marker positions such as shown in Figure 8.1 can be observed for the data from Experiment E0. Here, the green dot denotes the target marker position that had to be assessed, the black dots mark the positions where subjects placed the comparison markers over repeated trials. In order to conveniently describe the distribution of the data, it appears promising to compute a *Principal Component Analysis*.

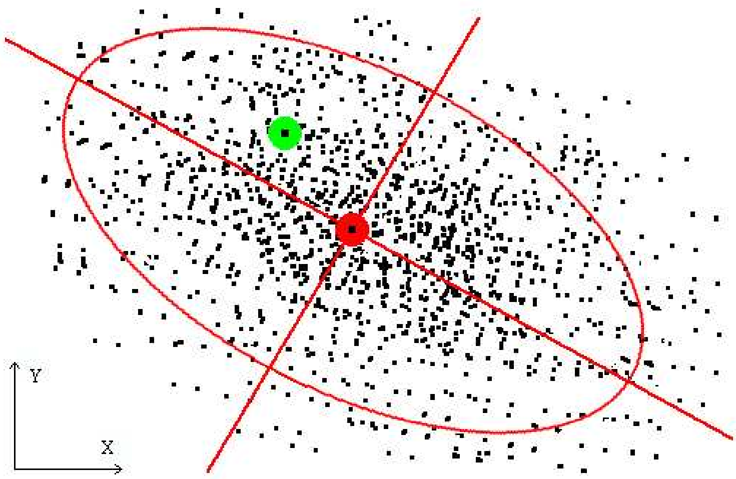


Figure 8.1: Sample distribution of comparison marker positions (black) and its mean (red) for a given target marker position (green). The ellipsis approximates the distribution of the comparison marker positions using principal component analysis (PCA).

Principal Component Analysis

The Principal Component Analysis (PCA), also known as the Eigen-XY analysis or Karhunen-Loeve expansion, is among the oldest and most widely used multivariate techniques. Originally introduced by Pearson (1907) and independently by Hotelling (1933), the basic principle of the method is to describe the variation of a set of multivariate data in terms of a set of uncorrelated variables each of which is a particular linear combination of the original variables. The new variables are derived in decreasing order of importance so that, for example, the first principal component accounts for as much as possible of the variation in the original data. Usually, only the first several such components are used to describe the original data while the others are cut off. The new variables can thus be used to summarise the data with little loss of information, thus providing a reduction in the dimensionality of the original data. This might be useful in simplifying later analyses, data interpretation and data parameterisation, for example for modelling purposes.

Let us consider the geometrical interpretation of this technique for the two-dimensional data of Experiment E0. If we assume that the positions of the comparison marker can be described by a bivariate normal distribution that reflects the greater radial than tangential deviation, these positions lie within an ellipsis, the so-called correlation ellipsis. Its shape and orientation represent the magnitude of the correlation. The PCA now implements the transformation of the original coordinate system into that of the principal components (axes) of the correlation ellipsis. The transformation consists of the translation of the coordinate system's origin to the center of gravity of the data distribution and of the orienting of the coordinate system along the principal components of the distribution, the Eigenvectors.

This means that, formally, this transformation is equivalent to the solution of an Eigenvalue problem where the first principal component yields the Eigenvector with the largest Eigenvalue λ_1. The second principal component is oriented orthogonal to the first and yields the second largest Eigenvalue λ_2 with $\lambda_2 < \lambda_1$ – and so on.

Mathematically, Eigenvectors are defined as

$$\lambda_i \cdot e_i = M * e_i, \tag{8.1}$$

i.e. the Eigenvectors of a Matrix are exactly those that, if multiplied by the Matrix M, constitute a multiple (the Eigenvalue λ) of themselves. In order to execute the transformation, the computation of the expected mean μ and the covariance matrix $C_{\vec{r}}$ of the original data distribution is required. For n data points $\vec{r}_i = (x_i, y_i)^T$ with $i = 1, ..., n$

$$\left.\begin{array}{l} \mu_x = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \\ \mu_y = \frac{1}{n} \cdot \sum_{i=1}^{n} y_i \end{array}\right\} \Rightarrow \vec{\mu}_{\vec{r}} = \begin{pmatrix} \mu_x \\ \mu_y \end{pmatrix} \qquad \textit{(expected mean)} \tag{8.2}$$

$$C_{\vec{r}} = \frac{1}{n} \cdot \sum_{i=1}^{n} (\vec{r}_i \cdot \vec{r}_i^{\,T} - \vec{\mu}_{\vec{r}} \cdot \vec{\mu}_{\vec{r}}^T) = \{c_{ij}\} \qquad \textit{(covariance matrix)} \tag{8.3}$$

In order to compute the Eigenvalues of the covariance matrix, the following Eigenvalue equation has to be solved

$$det(C_{\vec{r}} - \lambda \cdot I) = |C_{\vec{r}} - \lambda \cdot \mathbf{1}| = 0 \tag{8.4}$$

For two-dimensional data as the case in Experiment E0, this requires the solution of a quadratic equation and yields the Eigenvalues λ_1 and λ_2. The corresponding Eigenvectors V can subsequently be computed as

$$V = C_{\vec{r}} - \lambda \cdot I \tag{8.5}$$

The correlation ellipses that adequately describe the original data distribution are thus entirely determined by the expected means (ellipsis origin), the Eigenvectors (ellipsis orientation) and the Eigenvalues ("length" of the ellipsis' principal components).

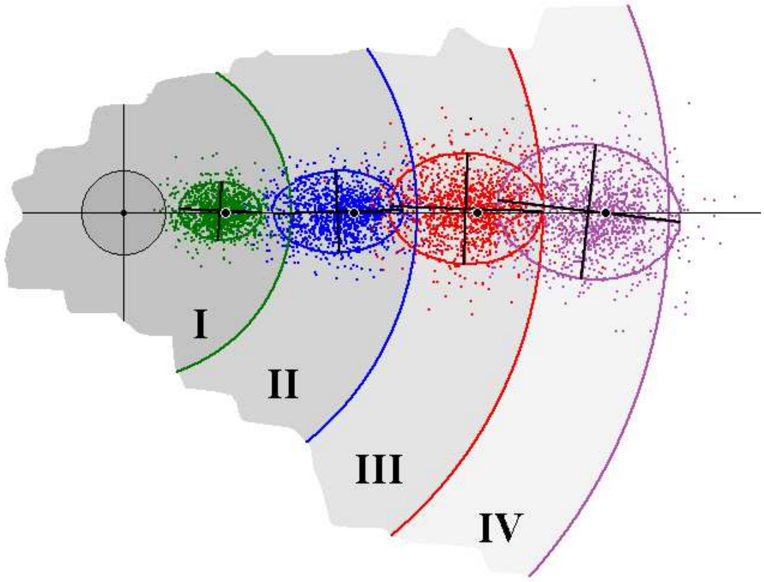


Figure 8.2: Distribution of comparison marker positions and their approximations using PCA for Eccentricities I–IV in Experiment E0.

If we now map all recorded data for the comparison marker positions with respect to a standard target marker position each for the eccentricity regions I-IV, the PCA will yield the four correlation ellipses shown in Figure 8.2. The black dots mark the standardised target marker position for the different eccentricities, the intersection of the principal components of the ellipses the center of gravity of the respective data distributions.

Finding a suitable, simplified description of the distribution of the data from Experiment E0 as realised with the PCA is only the first step in the development of the suggested computational model. In close relation to the determination of the shape and orientation of the data distribution in two-dimensional shape, we address the modelling of the distribution of the number of observations for particular comparison marker positions within the correlation ellipsis next. Although partly accounted for by the PCA technique already, the relative frequencies of the single observations have to be reflected in the model, in particular in the algorithmic generation of the "virtual" comparison marker positions. For the given empirical data of Experiment E0, a two-dimensional sample distribution of the comparison marker positions and their relative frequencies are shown in a three-dimensional diagram in Figure 8.3.

In a good approximation, the distribution of the relative frequencies can be described by a two-dimensional bivariate normal distribution. Mathematically, the density of the bivariate normal distribution is described by the following equation

$$\phi_N(x,y) \quad = \quad \frac{1}{2\cdot\pi|\Gamma|^{\frac{1}{2}}} \cdot e^{-\frac{1}{2}\left[\begin{smallmatrix} x-\mu_x \\ y-\mu_y \end{smallmatrix}\right]^T \Gamma^{-1}\left[\begin{smallmatrix} x-\mu_x \\ y-\mu_y \end{smallmatrix}\right]} \qquad \text{with} \tag{8.6}$$

$$\Gamma \quad = \quad cov\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{pmatrix} \qquad \text{where} \tag{8.7}$$

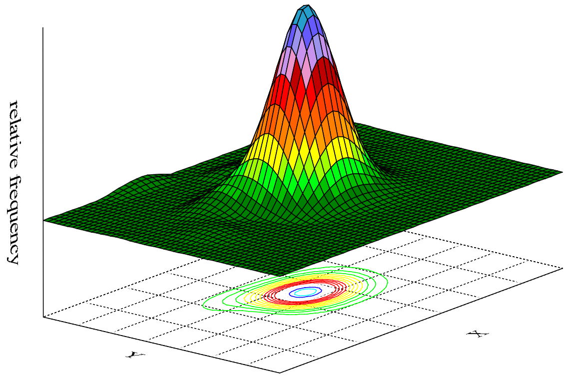


Figure 8.3: Sample distribution of comparison marker positions and their relative frequencies.

$$X = x_1, ..., x_n \quad \text{and} \tag{8.8}$$

$$Y = y_1, ..., y_n \quad \text{and} \tag{8.9}$$

$$|\Gamma| = \sigma_x^2 \cdot \sigma_y^2 - \sigma_{xy}^2 = (1-\rho^2) \cdot \sigma_x^2 \cdot \sigma_y^2 \quad \text{with} \tag{8.10}$$

$$\rho = \frac{\sigma_{xy}}{\sigma_x \cdot \sigma_y} \quad \textit{(correlation between X and Y)} \quad \text{and} \tag{8.11}$$

$$\sigma_{xy} = \sqrt{E[(X-\mu_x)\cdot(Y-\mu_y)]} \tag{8.12}$$

$$= \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (x_i - \mu_x) \cdot (y_i - \mu_y)} \quad \textit{(covariance)} \tag{8.13}$$

Such a distribution must now be oriented along the previously computed principal components of the correlation ellipses that span in the x–y plane. It further takes into account the Eigenvalues that reflect the variance in the data and determine the normal distribution's "width" so that the distribution finally constitutes a complete, appropriate representation of the empirical data of Experiment E0. The analyses of the empirical data of Experiment E0 further showed significantly different results for the positional assessment accuracy, depending on the eccentric location of the target marker. Consequently, the distributions must be individually adapted for the different eccentricity regions, using the relevant values – such as expected means, standard deviations, covariances, Eigenvalues and Eigenvectors – as computed in the previous statistical analyses and the PCA. Figure 8.4 visualises the accordingly parameterised empirical data for the eccentricity regions I–IV.

In the next step of the model design, we have to consider a suitable method of how to adequately generate virtual comparison marker positions, so that the properties of the simulated data equal those of the empirical data sets and their just-developed parame-

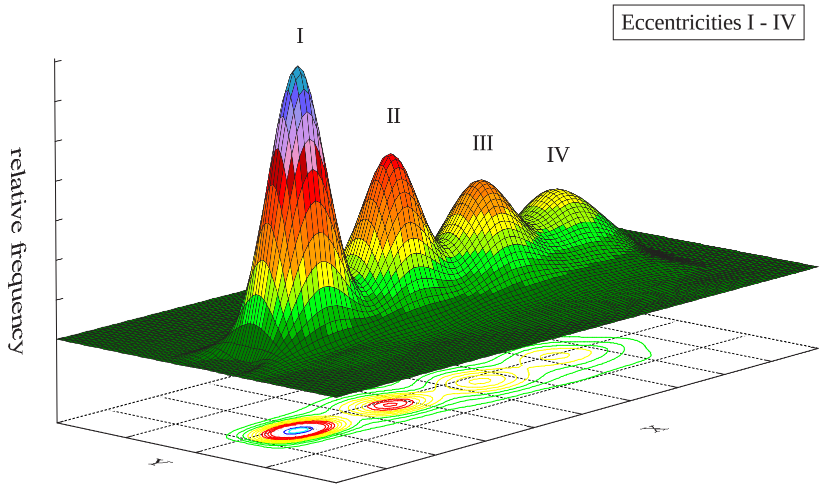


Figure 8.4: Distribution of the comparison marker positions and their relative frequencies for Eccentricities I–IV in Experiment E0.

terised descriptions. A promising approach is the reproduction of data described by the bivariate frequency distributions using a *Monte Carlo Simulation* method.

Monte Carlo Simulation

Basically, the Monte Carlo simulation method (MCS) provides approximate solutions to a variety of mathematical problems by performing statistical sampling experiments on a computer. The method applies to problems with no probabilistic content as well as to those with inherent probabilistic structure.

Technically, the fundamental idea of the MCS is to simulate a random process using random numbers. This concept requires a design of the simulation so that the random numbers – which are assigned to the results of the random process – yield corresponding probabilities of occurrence. If this can be achieved, the MCS presents a very reliable method for approximating data whose analytical computation is difficult or impossible. The following example illustrates the idea of the Monte Carlo simulation method.

Let is assume we want to determine some unknown number m. In order to apply the MCS, we have to define a random variable X with an expected mean of $E(X) = m$. We will further assume that, for example, we want to compute m as the dark grey shaded area under the graph shown in Figure 8.5. The graph describes the density of the standard normal distribution ϕ, given as

$$\phi(z) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma^2}} \cdot e^{-\frac{(z-\mu)^2}{2 \cdot \sigma^2}} \quad \text{with } \mu = 0 \text{ and } \sigma = 1 \tag{8.14}$$

$$= \frac{1}{\sqrt{2 \cdot \pi}} \cdot e^{-\frac{1}{2} \cdot z^2} \tag{8.15}$$

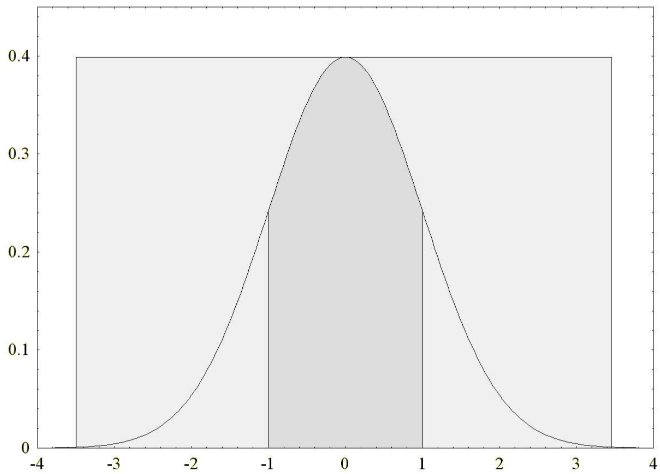


Figure 8.5: Density function of the standard normal distribution $N(0, 1)$. The area to be computed with probability $P(-1 < Z < 1)$ is shaded in dark, the rectangle enclosing (approx. 99.9% of) the distribution in light grey.

Unfortunately, no primitive function exists in $\mathbb{R}$ which makes the analytic solution of the equation and thus determining the area m impossible. Here, the MCS allows for the approximation of the result, using a statistical sampling technique. In order to determine m as defined above, i.e. the probability P of

$$P(-1 < Z < 1) \text{ with } Z \sim N(0, 1)^1 \tag{8.16}$$

the MCS yields a solution as follows: First, we chart the density function of the standard normal distribution from -3.5 to +3.5 (approximately 99.9% of all realisations of Z occur within that band which should ensure sufficient accuracy). Second, a rectangle that encloses the distribution is drawn with a width of 7.0 (from -3.5 to +3.5) and a height of $max_z \phi(z)$, i.e. the maximum of the density function. The area of the rectangle can obviously be computed to

$$7.0 \cdot (\underset{z}{max}\ \phi(z) - \underset{z}{min}\ \phi(z)) = 7.0 \cdot (0.3989 - 0.0009) = 2.7865 \tag{8.17}$$

We then randomly place dots within the rectangle, i.e. x- and y-coordinates have to be randomly generated. The x-coordinates must be uniformly distributed within [-3.5; +3.5] and the y-coordinates uniformly distributed within [0.0009; 0.3989423]. We now count the number of the "hits" in the relevant, i.e. dark grey shaded, area and compute the ratio of the "hits" and the total number of randomly generated coordinates. This ratio, multiplied by the rectangular area, gives the Monte Carlo simulated approximation of the relevant area, i.e. m. A sample run with 5000 random, uniformly distributed coordinates produces 1221 "hits" so that the MCS-approximated size of the area in question is

$$m = (1221/5000) \cdot 2.7865 = 0.6804 \tag{8.18}$$

[1]Density function of the standard normal distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$

The MCS generally yields very high quality approximations, for "large" simulations the approximation error converges toward 0. Among all numerical methods that rely on N-point evaluations in M-dimensional space to produce an approximate solution, the Monte Carlo method has absolute error of estimate that decreases as $N^{-1/2}$ whereas, in the absence of exploitable special structure all other methods have errors that decrease as $N^{-1/M}$ at best.

Rather than for the approximation of primitive functions as in the example above, the Monte Carlo simulation method presents a very convenient tool with respect to the simulation in the scope of the current investigation. We previously described the empirical data of Experiment E0 by bivariate frequency distributions with the characteristics of a normal distribution and determined the orientation and typical statistical values such as expected mean and standard deviation by a principal component analysis.

The MCS now allows us to generate random coordinates x and y whose distribution is equivalent to that of the empirical data or, more accurately, to that given by the bivariate normal frequency distribution that describes the empirical data. This is achieved by generating an extra random z-coordinate for each (random) pair of x and y. The x- and y-coordinates are considered valid coordinates only when the associated z is located "under" the bivariate normal frequency distribution (see Figure 8.6). Consequently, this leads to the generation of x- and y-coordinates whose frequency distribution simulates the empirically given example. This procedure thus simulates comparison marker positions for given target marker positions in accordance with the subjects' assessments. Due to the significant empirical differences found for position assessment in Experiment E0 for the factor eccentricity, the model employs different parameters for the four eccentricity

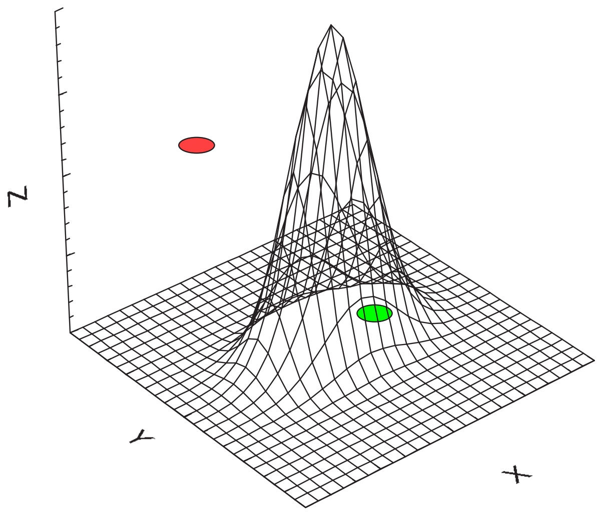


Figure 8.6: Density function of a bivariate standard normal distribution. The green marker at a randomly MCS-generated position (x,y,z) can be labelled "valid" because it is located "under" the distribution. The red marker is obviously not.

regions I–IV. Here, the specific characteristics of the PCAs and the frequency distributions are taken into account for the MCS modelling of the simulated comparison marker positions.

Recall that we hypothesised that the assessment of line segment length and orientation is a process strongly influenced by the assessment of the line segments' end point information. Thus, the goal of the simulation is to compare line segment length and orientation assessments from Experiments E1 and E2, respectively, to "virtual" comparison line segment lengths and orientations. These virtual line segments are constituted by their simulated end points using the MCS method explained above. As the steps (b)-(d) of the model implementation (s. page 117) suggest, an MCS has to be computed for the two end points that determine the target line segment, yielding the simulated end points of the comparison line segment (steps (b) and (c)). Computing the difference (step (d)) between these points yields the length and orientation of the model comparison line segments. In the subsequent statistical analyses the length and orientation divergences can be computed (step (e)) in analogy to those conducted in Experiments E1 and E2, respectively. The comparison of the model results to the empirical ones (step (f)) finally yields insight into the performance and the possible adequacy of the model. The latter two steps will now be discussed in the following Section 8.3.

8.3 Model Results and Discussion

Let us now consider how the proposed model scores. For the relevant dimensions, comparison line segment length and comparison line segment orientation, analyses of variance were conducted to establish possible effects of the factors eccentricity of presentation, target line segment length and target line segment orientation on the respective assessment accuracy. Furthermore, the corresponding mean values for the various factor levels were computed. A subsequent direct comparison of the empirical and simulated data enables us to validate whether the model correctly accounts for the effects and their magnitudes established in Experiments E1 and E2.

As the model approach does not yield values for RT, only the simulated length deviations $MDL_{(p)}$ and the orientation deviations MDO of the simulated comparison from the target line segment will be investigated. The underlying data was computed according to the previously described modelling procedure and constituted data sets of the same structure as recorded in the Experiments E1 and E2. Furthermore, data was simulated for the same combinations of the factors eccentricity, target line segment length and orientation. The number of repeated measures and (here "virtual") subjects was identical, too, in order to ensure equal conditions for the comparison of the simulated and the empirical data sets.

Modelling Length Assessment

In analogy to the analyses in Experiment E1, both the absolute (positive) and the directional length deviations, MDL_p and MDL, respectively, will be considered.

MDL$_p$: A three-way analysis of variance established significant main effects for the factors eccentricity ($F(3;33) = 72.88; p < 0.001$) and target line segments length ($F(2;22) = 122.17; p < 0.001$) on MDL$_p$. Averaging data over lengths and orientations (for all "virtual" subjects), modelled comparison line segment lengths deviate from the target lengths by 13.7% for Eccentricity I, 18.0% for Eccentricity II, 21.6% for Eccentricity III and 26.8% for Eccentricity IV. A cumulation of data over the factors eccentricity and orientation yields that subjects incorrectly adjust the length of the comparison line segment by 38.4% (short), 12.9% (intermediate) and 7.3% (long) on average. The factor orientation does not yield a significant main effect on MDL$_p$ ($F(2;22) = 1.29; p = 0.296$).

In addition, the interaction between eccentricity and target line segment length reaches significance ($F(6;66) = 31.42; p < 0.001$). This can be attributed to the fact that DL$_p$ constantly increases with greater eccentricities for short and intermediate line segments, whereas it remains level for long line segments. For short line segments, DL$_p$ is computed to be 0.27, 0.35, 0.41, 0.47, for intermediate length 0.08, 0.13, 0.16. 0.19 and for long line segments 0.06, 0.07, 0.08, 0.09 – each for the respective Eccentricities I–IV. Furthermore, the interaction between eccentricity and target line segment orientation shows a significant effect on MDL$_p$ ($F(6;66) = 2.39; p = 0.0376$). No other interactions have significant effects on MDL$_p$. Figure 8.7 shows the positive relative length deviation MDL$_p$ as a function of eccentricity and target line segment length.

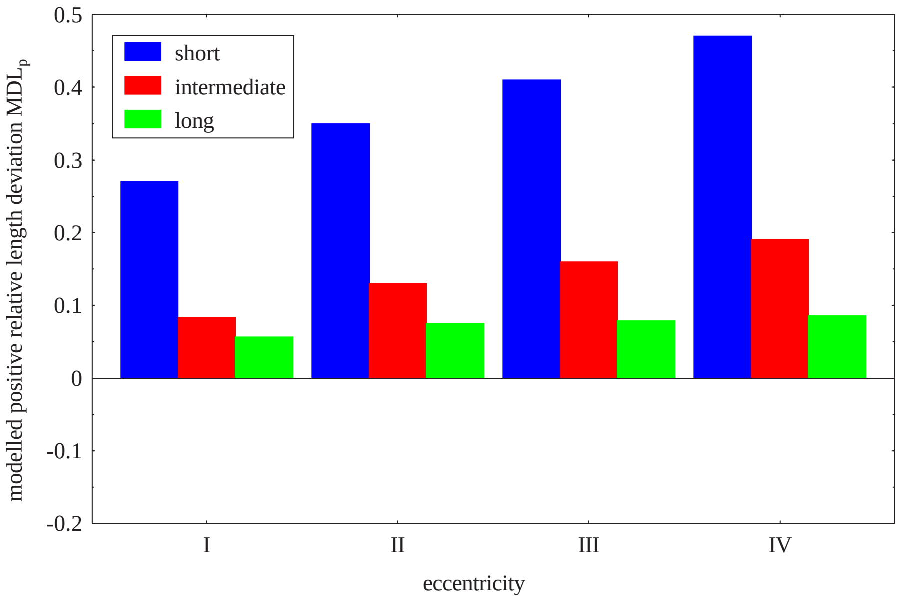


Figure 8.7: Modelled positive relative deviation MDL$_p$ of the length of the comparison from the target line segment as a function of Eccentricity I–IV and target line segment length (short, intermediate, long).

MDL: An identical multi-factorial analysis of variance as for MDL$_p$ is conducted for MDL, the dependent variable that additionally contains directional information on the length deviation of the comparison from the target line segment length. The analysis yields a significant main effect of the factor eccentricity on MDL ($F(3;33) = 48.56; p < 0.001$). The target line segment length is generally overestimated, increasingly so with increasingly eccentric presentation. The overestimation effect reaches the following values: 2.7% when the target line segment is presented within the eccentricity region I, 9.7% in eccentricity region II, 17.0% in eccentricity region III and 19.0% in eccentricity region IV. Another significant main effect on MDL can be found for target line segment length ($F(2;22) = 239.49; p < 0.001$). If we average over eccentricity and orientation, a mean overestimation of 28.3% for short and of 6.0% for intermediate line lengths emerges. Long line segments are overestimated by 2.0% on average. Again, no significant main effect for the factor orientation can be observed ($F(2;22) = 1.26; p = 0.304$). The further analysis shows that the interaction between eccentricity and target line segment length, which proved significant for MDL$_p$, prevails for MDL ($F(6;66) = 31.28; p < 0.001$). Figure 8.8 illustrates the relative length deviation MDL as a function of eccentricity and target line segment length.

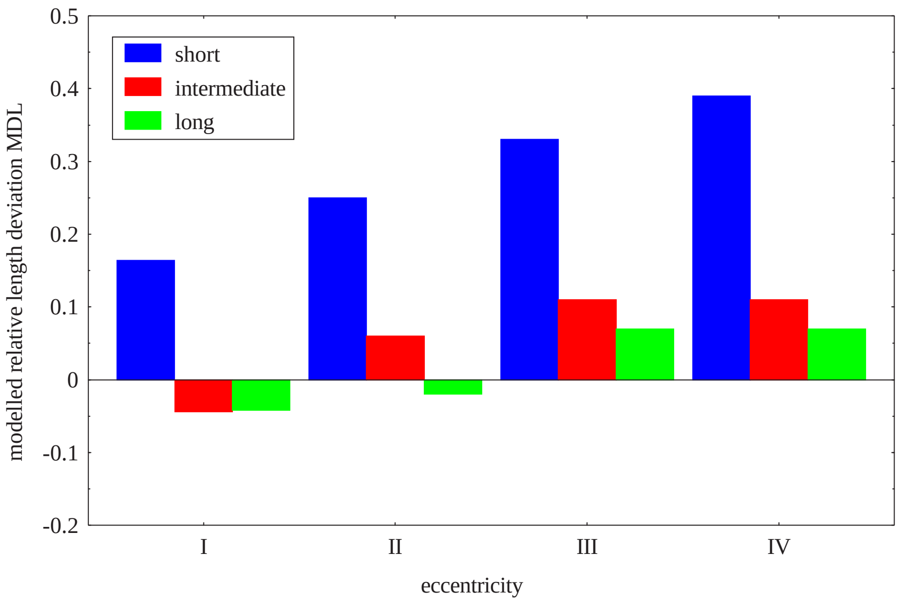


Figure 8.8: Modelled relative deviation MDL of the length of the comparison from the target line segment as a function of eccentricity and target line segment length.

How can we now rate the performance of the implemented model for the assessment of line segment lengths? In order to achieve reliable conclusions in this respect, the empirical results of Experiment E1 and the simulated model data are subjected to further statistical analysis. With the introduction of the between-subjects factor "experiment", i.e. Experiment E1 vs. simulation, the two data sets can be compared and checked for correspondence. The respective analysis yields no significant effect for the factor experiment on the relevant dependent variables (M)DL$_p$ ($F(1;22) = 0.03; p = 0.861$) and (M)DL ($F(1;22) = 2.15; p = 0.157$). These promising results indicate that no significant differences exist between the simulated and the empirical data sets, i.e. that the modelling approach chosen might indeed be suitable to adequately reproduce the data as measured in Experiment E1.

Further support is obtained from the comparison of the results of the various analyses

	Experiment E1	Model	Comp./Diff.
Significant effect of ... on (M)DL$_p$			
• ECC	+	+	⊕
• LEN	+	+	⊕
• ORI	-	-	⊕
• ECC × LEN	+	+	⊕
• ECC × ORI	-	+	⊖
• LEN × ORI	-	-	⊕
• ECC × LEN × ORI	-	-	⊕
Mean (M)DL$_p$ in/for ...			
• ECC I	16.6%	13.7%	2.9%
• ECC II	18.6%	18.0%	0.6%
• ECC III	21.9%	21.6%	0.3%
• ECC IV	23.8%	26.8%	3.0%
• LEN short	31.8%	38.4%	6.6%
• LEN intermediate	17.2%	12.9%	4.3%
• LEN long	11.8%	7.3%	4.5%
Significant effect of ... on (M)DL			
• ECC	+	+	⊕
• LEN	+	+	⊕
• ORI	-	-	⊕
• ECC × LEN	+	+	⊕
• ECC × ORI	-	-	⊕
• LEN × ORI	-	-	⊕
• ECC × LEN × ORI	-	-	⊕
Mean (M)DL in/for ...			
• ECC I	+4.8%	+2.7%	2.1%
• ECC II	+9.6%	+9.7%	0.1%
• ECC III	+15.7%	+17.0%	1.3%
• ECC IV	+17.9%	+19.0%	1.1%
• LEN short	+28.9%	+28.3%	0.6%
• LEN intermediate	+8.9%	+6.0%	2.9%
• LEN long	-1.9%	+2.0%	3.9%

Note: ECC – eccentricity region; LEN – target length; ORI – target orientation

Table 8.1: Summary of the results of modelling line segment lengths in comparison with the empirical findings of Experiment E1.

of variance conducted for Experiment E1 and the model data, respectively. In Table 8.1, all main and interaction effects tested on the empirical and the simulated data are listed (for details, see Sections 6.2 and 8.3). In the first column, the type of effect on (M)DL$_{(p)}$ is shown, the "+" or "-" in the second and third column marks whether the effect was significant or not for the empirical and simulated data, respectively. The ⊖ or ⊕ in the last column indicates the (non-) conformity of the significance levels of the two data sets. Obviously, a convincing correspondence exists between the levels of significance that the data from Experiment E1 and the model data yielded. All but one effect (2-way interaction of eccentricity and orientation (ECC × ORI) for (M)DL$_p$) of the empirical data could be reproduced in the simulation.

However, the analyses of variance do not yield reliable information concerning the "directions" and the magnitudes of the differences in the dependent variables for the factor levels. Even two "inverse" data sets could produce analogous significance effects. Different magnitude scales in the two data sets would not be accounted for by the within-subjects analysis of variance either. It is therefore essential to closely examine the absolute mean values and their ranks for the relevant factor levels in the empirical and simulated data and to directly compare them. Only then can reliable statements regarding the conformity of the data – and thus the rating of the model performance – be made.

Apart from the lists of effects which reached significance (or not) in Experiment E1 and the simulation, Table 8.1 charts the absolute mean values for (M)DL$_p$ and (M)DL (for details, see Sections 6.2 and 8.3). The differences between these values for the empirical and model data are generally very small, ranging from 0.1% to a maximum of only 6.6%. On average, MDL$_p$ diverges from DL$_p$ by 3.1% and MDL from DL only by a mere 1.7%. This very accurate approximation confirms that the simulation suitably models the absolute empirical values. This observation is further visualised in Figures 8.9 and 8.10. Here, data from Figures 8.7 and 6.4 and Figures 8.8 and 6.5, respectively, is merged to facilitate the comparison. The figures do not only show the close resemblance of the absolute mean values, but also indicate that the model data ranks are equivalent to those of the empirical data. These more qualitative findings are supported by statistical evidence: The analysis of variance yields no significant interaction effects of the (between-subjects) factor experiment and the factor eccentricity, target orientation or length on the relevant dependent variables (M)DL$_P$ and (M)DL.

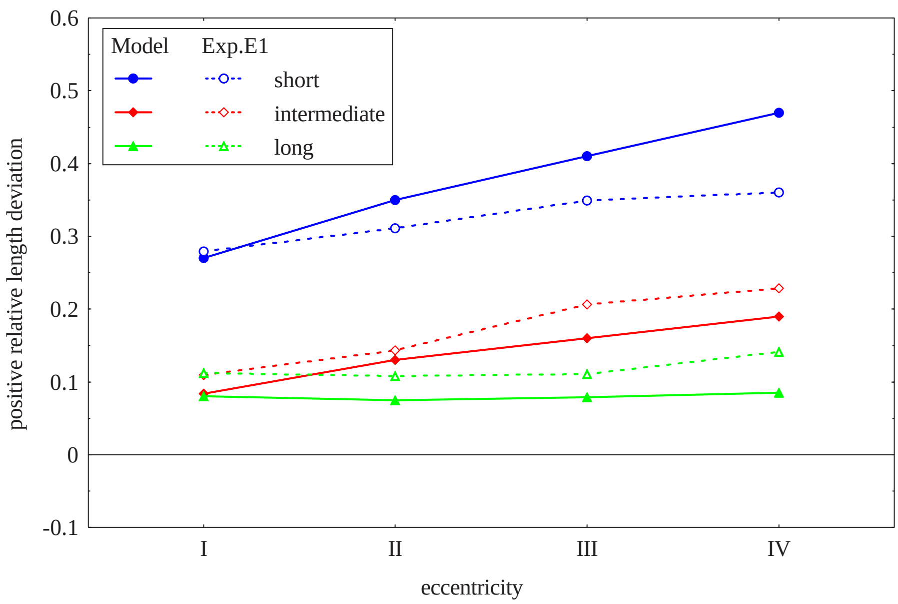


Figure 8.9: Comparison of the empirical and simulated positive relative deviations DL$_p$ and MDL$_p$ for the Eccentricities I–IV and the target line segment lengths (short, intermediate, long).

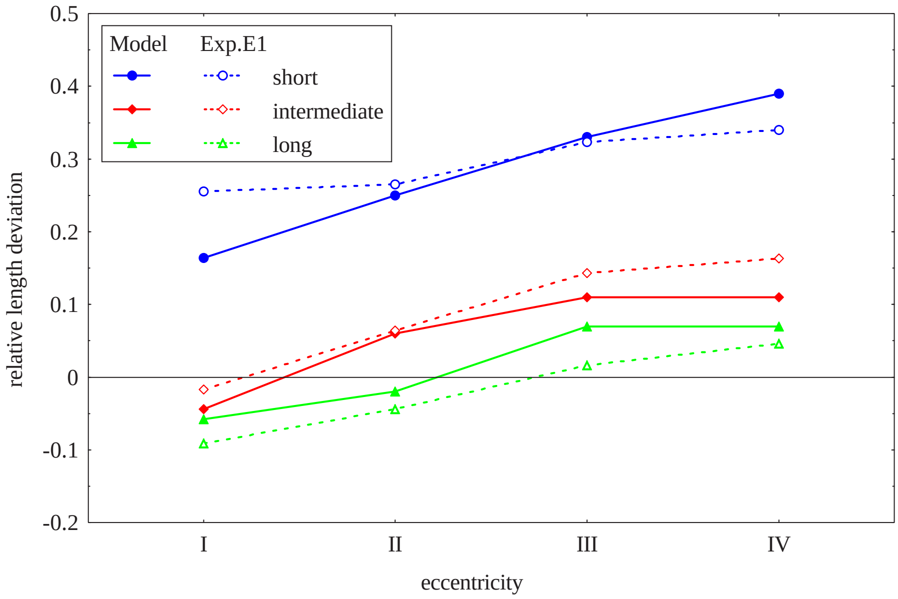


Figure 8.10: Comparison of the empirical and simulated relative deviations DL and MDL for the Eccentricities I–IV and the target line segment lengths (short, intermediate, long).

In summary, we observe that an additional analysis of variance does not reveal a significant effect for the factor experiment on the relevant dependent variables. The separate analyses of variance result in nearly identical effects for the empirical and simulated data, and both the absolute values of the characteristic means and their ranks for the model data show a close resemblance to those of Experiment E1. Taking these findings into account, it appears that the chosen modelling approach is indeed *suitable* for adequately reproducing the manifold aspects involved in the peripheral perception of line segment lengths. The model's convincing replication performance gives rise to the assumption that we possibly correctly identified perception mechanisms involved in the assessment of line segment lengths – namely the essential contribution of line segments' end point information. Furthermore, we adequately formalised these mechanisms in the implemented simulation.

We will now examine, whether these promising assumptions also hold for the peripheral assessment of line segment orientation and thus yield even more support for the proposed model and the implications for the underlying perception principles.

Modelling Orientation Assessment

Again, data will first be subjected to a three-factorial analysis of variance in order to account for the three independent variables eccentricity region, target line segment length and orientation. In analogy to the analyses in Experiment E2, the effects of these factors are tested here on the dependent variable modelled orientation deviation MDO of the target line segment from the comparison line segment.

The analysis of variance yields significant main effects for two of the three factors. First, the effect of eccentricity on the modelled orientation deviation MDO reaches significance

($F(3;33) = 21.29; p < 0.001$). Similar to the eccentricity effects in the empirical data, the "virtual" subjects' performance deteriorates the further the target line segment appears in the periphery. On average, the simulated orientation of the comparison line segment deviates from that of the target line segment by 5.5 degrees in Eccentricity I, by 7.4 degrees in Eccentricity II, by 7.7 degrees in Eccentricity III and by 8.7 degrees in Eccentricity IV.

Second, the factor target line length is once again found to have a highly significant effect on MDO. The respective analysis yields a significance level of ($F(2;22) = 118.99; p < 0.001$), manifested in a greater mean orientation deviation for short line segments (9.8 degrees) than for intermediate ones (7.2 degrees), and in an again smaller MDO for long line segments (4.7 degrees). Figure 8.11 shows MDO as a function of the eccentricity region (I–IV) and the length of the target line segments (short, intermediate, long).

In contrast to the empirical findings, the third factor, target line orientation, does not show a significant effect on MDO ($F(2;22) = 1.07; p = 0.360$). Independent of the orientation of the target line segment, the average orientation deviation measures approximately 6.5 degrees. Figure 8.12 shows MDO for all eccentricity regions (I–IV), separated for the three possible orientations of the target line segments (horizontal, oblique, vertical).

One of two interactions that reach the significance level is that between target line segment length and orientation ($F(4;44) = 2.73; p = 0.041$). Here, this effect must be attributed to the fact that, for horizontal and vertical target orientations, MDO does not significantly differ between short and intermediate target line segment length, whereas this is the case for oblique line segments and for all other comparisons between different line segment lengths, irrespective of their orientation. Unlike the interaction between eccentricity and target line segment length in Experiment E2, this interaction reaches significance in the simulation ($F(6;66) = 6.49; p < 0.001$). It can be observed that MDO for short target line segments does not significantly differ between the different eccentricities,

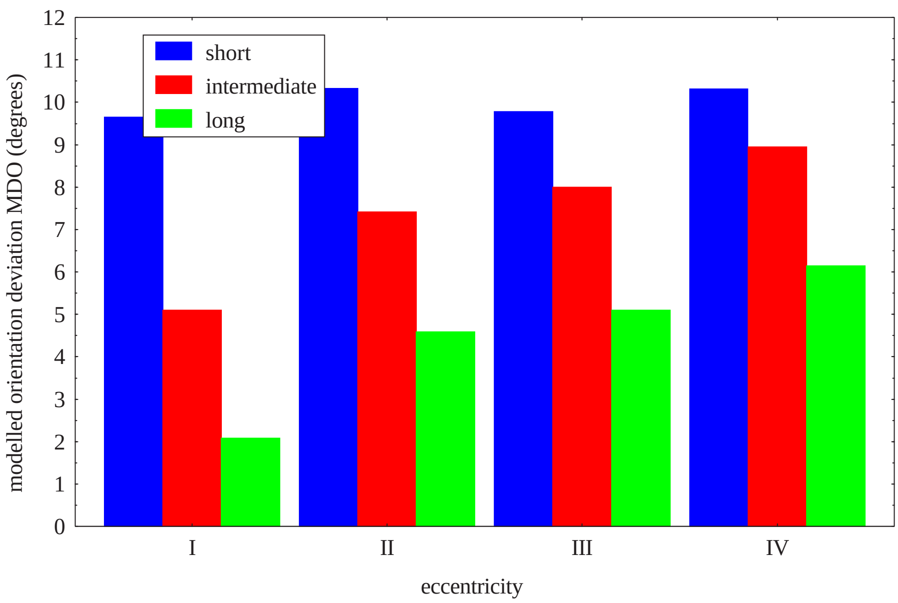


Figure 8.11: Modelled orientation deviation MDO of the comparison from the target line segment as a function of eccentricity and target line segment length.

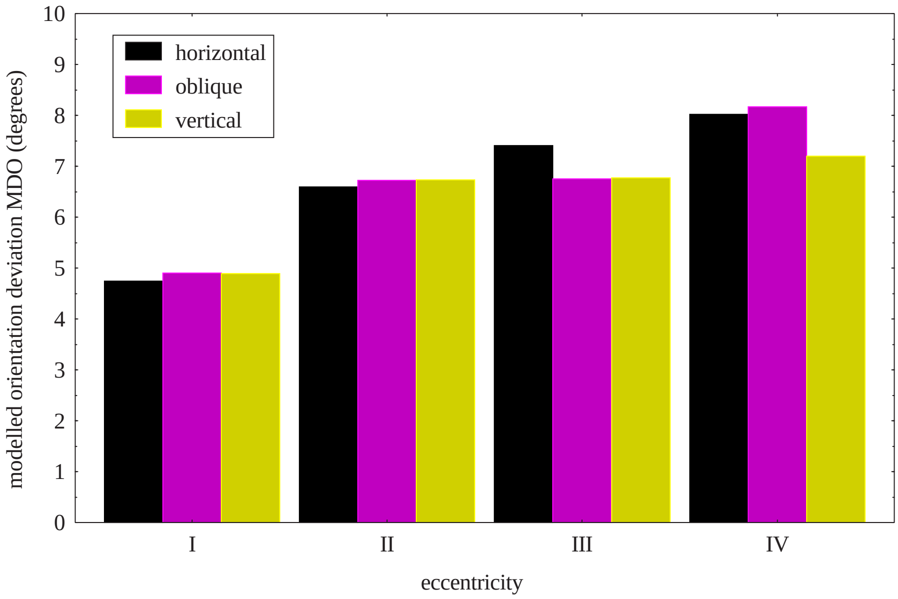


Figure 8.12: Modelled orientation deviation MDO of the comparison from the target line segment as a function of eccentricity and target line segment orientation.

whereas MDO does for intermediate and long line segments: The modelled orientation deviation almost linearly increases from eccentricity region I–IV and MDO shows significant differences between the separate eccentricities. All other two-way interactions and the three-way interaction between eccentricity, target line segment length and orientation do not show significant effects on the modelled orientation deviation MDO.

In order to evaluate the model performance with respect to the reproduction of the empirical orientation assessment data, the same comparison procedure will be followed as before when modelling length assessment. When comparing the empirical data from Experiment E2 and the simulated data, the then introduced between-subjects factor "experiment" yields no significant effect on (M)DO ($F(1; 22) = 2.88; p = 0.124$). This suggests that no significant differences exist between the simulated and empirical data sets and, thus, that the chosen modelling approach might indeed be adequate to account for the data measured in Experiment E2 as well.

In analogy to the previous comparison, the upper part of Table 8.2 contains the results of the separate multi-factorial analyses of variance as conducted in Experiment E2 and for the simulated data. It emerges that the model could successfully reproduce the majority of "empirical" effects. However, the significant main effect of the orientation of the target line segment on DO in Experiment E2 is "lost" in the simulation. In contrast, the simulation "gains" an interaction effect between eccentricity and target length (ECC × LEN) on MDO, which is not significant in the empirical data. The results further indicate that the interaction between target length and orientation (LEN × ORI) – although present both in Experiment E2 and the simulation – becomes significant for different reasons (see above).

The lower bottom part of Table 8.2 charts the absolute mean values for (M)DO (for details see Sections 7.2 and 8.3). As before, the differences between these values for the empirical and model data are generally very small, ranging from 0.3^o to a maximum of only 2.4^o. On average, MDO diverges from DO by only 0.8^o when data is aggregated over eccentricity, by 1.3^o (over target length) and by 1.0^o (over target orientation). These highly accurate approximations initially suggest that the simulation suitably models the absolute empirical values. In general, this observation is true and holds for most values. Taking the previously found differences in the statistical analyses into account, a closer inspection of the data reveals, however, that the simulation does not as accurately model all aspects of orientation as those of length assessment. These differences become somewhat more obvious in Figures 8.13 and 8.14. Here, data from Figures 8.11 and 7.3 and Figures 8.12 and 7.4, respectively, is merged to facilitate the comparison.

Thus, Figure 8.13 illustrates that the model data very closely resembles the empirical data from Experiment E2 with respect to their absolute values and their ranks for the different eccentricities and the different levels of target line segment length. The model data is shifted considerably upwards only for short line segments, but still maintains the shape of the empirical curve. However, this results in a significant interaction effect of the (between-subjects) factor experiment and the factor target length on the dependent variable (M)DO ($F(2; 44) = 18.21; p < 0.001$).

Differences between empirical and model data become more pronounced in Figure 8.14, where the orientation deviation for the eccentricity regions I–IV is separately charted for

	Experiment E2	Model	Comp./Diff.
Significant effect of ... on (M)DO			
• ECC	+	+	⊕
• LEN	+	+	⊕
• ORI	+	-	⊖
• ECC × LEN	-	+	⊖
• ECC × ORI	-	-	⊕
• LEN × ORI	+	+	⊕
• ECC × LEN × ORI	-	-	⊕
Mean (M)DO in/for ...			
• ECC I	6.0^o	5.5^o	0.5^o
• ECC II	6.4^o	7.4^o	1.0^o
• ECC III	7.1^o	7.7^o	0.6^o
• ECC IV	7.5^o	8.7^o	1.2^o
• LEN short	7.4^o	9.8^o	2.4^o
• LEN intermediate	6.9^o	7.2^o	0.3^o
• LEN long	5.8^o	4.7^o	1.1^o
• ORI horizontal	5.4^o	6.5^o	1.1^o
• ORI oblique	7.3^o	6.6^o	0.7^o
• ORI vertical	7.7^o	6.4^o	1.3^o

Note: ECC – eccentricity region; LEN – target length; ORI – target orientation

Table 8.2: Summary of the results of modelling line segment orientations in comparison with the empirical findings of Experiment E2.

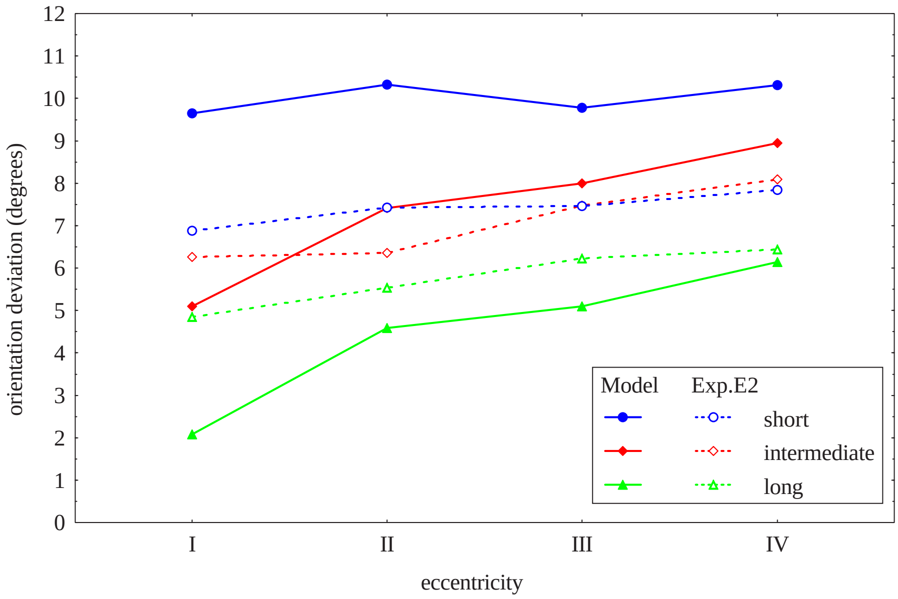


Figure 8.13: Comparison of the empirical and simulated orientation deviations DO and MDO for the Eccentricities I–IV and the target line segment lengths (short, intermediate, long).

the different orientations of the target line segment. Although the absolute differences between the two data sets are, according to Table 8.2, quite small, the lack of the statistically significant effect of the target orientation on MDO is well visible between the "empirical" and "model graphs" for horizontal target line segments: Whereas subjects in Experiment E2 could (significantly) more accurately assess the orientation of horizontal target line segments than that of oblique or vertical ones, the model does not account for this dependence. All three model curves do not vary significantly and more closely resemble those of the empirical oblique and vertical graphs. Consequently, an analysis of variance yields a significant interaction effect between the (between-subjects) factor experiment and the factor target orientation ($F(2; 44) = 7.89; p = 0.001$).

In summary, we observe that an additional analysis of variance does not reveal a significant effect for the factor experiment on the relevant dependent variables (M)DO. However, interaction effects between experiment and orientation and between experiment and target length reach significance, indicating deficits of the model in accounting for all aspects of simulating the orientation assessment of line segments. This is further supported by the separate analyses of variance that result in identical (non-) significant effects for the empirical and simulated data for all but the above-mentioned factors. In accordance with these findings, both the respective absolute means and their ranks for the model data show a close resemblance to those of Experiment E2 as far as the simulation of the eccentricity effects and the dependence of MDO on the target line segment length is concerned. The simulation does not convincingly reproduce the empirical data with respect to the influence of the target orientation on (M)DO.

Altogether, the chosen model still presents quite a *successful* approach to reproduce the essential aspects involved in the peripheral perception of line segment orientation. Its main *deficit*, however, is the inability to adequately account for the influence of orientation

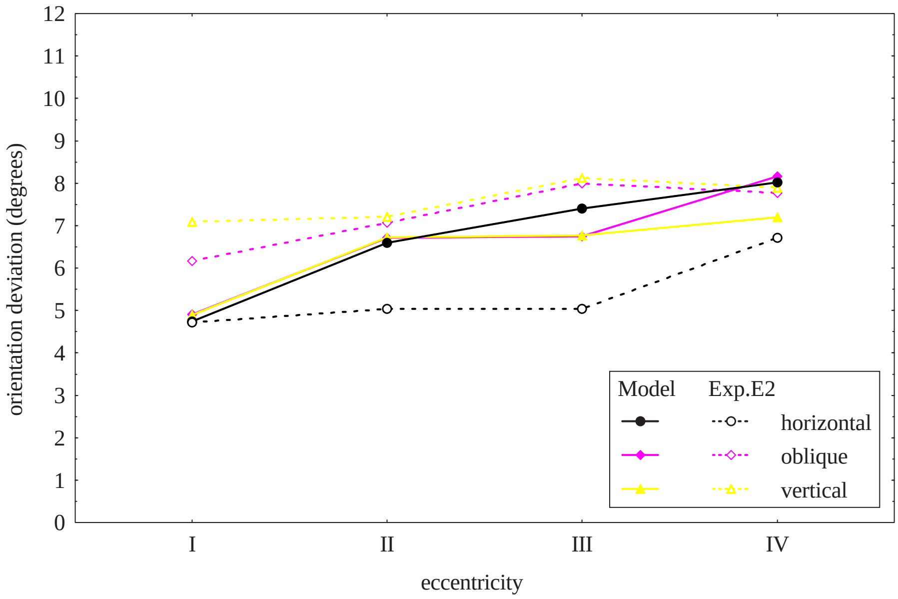


Figure 8.14: Comparison of the empirical and simulated orientation deviations DO and MDO for the Eccentricities I–IV and the target line segment orientations (horizontal, oblique, vertical).

of the target line segment on the accuracy of the orientation assessment. The model performance thus allows us to conclude that we possibly correctly identified *some* of the essential perception mechanisms involved in the assessment of line segment orientation, namely the essential contribution of line segments' end point information, as was the case for the assessment of line segment length as well. However, peripheral orientation assessment appears to be guided by *additional* mechanisms. These might take other line segment information into account, presumably segment-inherent, and thus lead to more diversified empirical findings, in particular with respect to orientation dependences. The implemented model approach therefore seems to be primarily adequate for simulating peripheral lengths rather than peripheral orientation assessments. Nevertheless, it still allows for the latter in good approximation.

8.4 Summary and Conclusions

Let us recall that the overall goal of the investigation is to identify and better understand the processes that characterise the visual perception and the assessment of line segments and their essential dimension(s). As a promising strategy to achieve this goal, a data driven, explorative bottom-up approach is chosen. First, fundamental mechanisms governing the specific task solution are explored in isolation. If, as a result, the various findings can be integrated appropriately, this might ideally lead to the understanding of the whole, possibly rather complex perception process.

Inspired by earlier research that suggested the influence of peripheral vision as one of such fundamental factors on the assessment of line segments, the previous chapters aimed at an in-depth understanding of eccentricity effects on the visual perception of line segments. In particular with respect to length and orientation assessment, the hypothesised *decomposition* strategy was explored. Rather than only collecting psychophysical data, the design and sequence of the studies conducted in this respect were chosen in order to primarily meet the following criteria:

- A maximum validity of the empirical results must be ensured. This can be questioned in several other studies where distractor tasks were used to indirectly generate (quite unnatural) peripheral viewing conditions that still could not be reliably monitored. In this case, the application of a sophisticated eye-tracking system creates natural, realistic viewing conditions for subjects and yields transparent, reliable data for the experimenter.

- The sequence of the Experiments E0–E2 was chosen as it ideally reflects the initial *decomposition* hypothesis: When we assume that *end point information is vital for the assessment of line segment attributes such as length and orientation*, it might thus be possible to directly infer *line segment length or orientation accuracy from position assessment accuracy*. Such a *decomposition* of peripheral perception processes then encourages the development of an analogous model to simulate the line segment length and/or orientation perception principles based on peripheral positional assessment modelling. This model of eccentricity effects may later be integrated into the more complex model of simultaneous line segment comparison.

According to these specifications, the Experiments E0, E1 and E2 were conducted and, indeed, yield great support for the above-mentioned hypothesis.

With respect to location assessment in peripheral vision, the results from Experiment E0 suggest that the assessment of *position* is governed by *two distinct processes*. One is responsible for the assessment of the *direction* where the target in question is situated, a process that obviously works quite accurately and more or less independent of the eccentric position of the target. The second process involved determines the *distance* between fixation point and target. This process yields less accurate judgements as the radial position of the target is significantly underestimated. Furthermore, this process is eccentricity-dependent and shows deteriorating assessment accuracy for the radial target position with increasing peripheral viewing. On aggregate, the combination of these two processes yields positional judgements that are dominated by the distance component and results in a perceived *position of the target marker that is shifted in the direction of the fixation point*, but shows very little directional divergence. In addition, the statistical analysis demonstrated that *no* significant difference exists whether the target marker is positioned horizontally or vertically, relative to the fixation point. Taking the ellipsoidal shape of the retina and the ovoid shape of the (binocular) visual field into account (both with the horizontal axis being the longer), this finding is rather unexpected. Due to the asymmetry, the preferred horizontal orientation of the visual field and the further range of receptors along this axis could be well expected to lead to a better position assessment accuracy along the horizontal than along the vertical meridian. However, this is obviously not the case.

In Experiment E1, the assessment of the length of peripherally viewed line segments demonstrates that the lengths of the target line segments are generally *overestimated*. This overestimation effect significantly increases the further the target line segment is displayed in the periphery. Whereas the factor target line segment orientation does not exert a significant effect on the length assessment accuracy, the target length does: The longer the target line segments are, the more accurately their length can be assessed. Based on the observation regarding location assessment in Experiment E0 and the assumption that the line segment's end points play an important role for the length assessment, a possible explanation for the (eccentricity) effects on line segment length assessment reported in Experiment E1 can be formulated. In detail, the explanation of the overestimation of line segment lengths in Experiment E1 is based on the finding of Experiment E0, that the actual position of the target marker is perceived as being shifted towards the fixation point (underestimation of the radial target marker position). In contrast, very little divergence between the tangential position of the comparison and the target marker was noticed. We now transfer these observations and assume that the principles of location assessment apply to the peripheral perception of line segment lengths as well. It then emerges that, when memorising a line segment peripherally perceived, subjects develop a mental model of a line segment of approximately the original (target) length, but *shifted towards the fixation point*. This (mental) "shift" or dislocation of the line segment towards the observer leads to an elongation of the line segment when its mental model is recalled in the reconstruction phase of the experiment, i.e. when the length of the comparison line segment has to be adjusted. This is due to the principle of size/length constancy which states that the size/length of objects seems to increase when they are moved towards the observer.

The third experiment in this series, where eccentricity effects on the assessment of line segment orientation are investigated, yields findings analogous to those of Experiment E1. Again, the factor eccentricity exerts a significant effect – here on the orientation deviation DO – and results show a markedly better orientation assessment for more foveal than for more eccentric presentation locations of the target line segment. Furthermore, the orientation of longer target line segments can also be assessed more accurately. In contrast to the findings of Experiment E1, the factor target line segment orientation exerts an additional significant effect on DO. The discussion of these results again rendered the previously introduced approach promising, to think of orientation assessment also as a process determined by the perceived locations of the line segments' end points. If we take into account the findings for the location assessment from Experiment E0, these could also be reflected in and probably account for some of the results of Experiment E2. For example, due to the greater variance along the radial rather than the tangential axis in the location assessment task of Experiment E0, a considerable variation in the orientation assessment must be expected – and could indeed be observed in Experiment E2. Thus, this approach again seems plausible and intuitively suggests an account for the orientation deviations observed in Experiment E2.

With respect to the subsequent development of a simulation, the analogous results of the Experiments E1 and E2 and possibly related principles behind peripheral length and orientation assessment of line segments encourages the "integrated" modelling, based on the findings from Experiment E0. The goal of the simulation is to compare line segment length and orientation assessments from the Experiments E1 and E2, respectively, to "virtual" comparison line segment lengths and orientations. These virtual line segments are constituted by their simulated end points using the Monte-Carlo Simulation (MCS) method. The MCS takes into account the specific characteristics of the frequency distributions of the empirical comparison marker positions, manifested and parameterised by means of a principal component analysis (PCA).

In summary, we observe that statistical analyses do not reveal significant differences between empirical and simulated data, produce nearly identical (non-) significant effects for the empirical and simulated data and both the absolute values of the characteristic means and their ranks for the model data show a close resemblance in particular to those of Experiment E1. With regard to Experiment E2, the model cannot be rated as quite as convincing in all aspects. Although, on aggregate, performance can still be rated as very good, it has some deficits with respect to a correct representation of orientation effects and the reproduction accuracy of some absolute statistical values. Irrespective of these (minor) disadvantages, taking the findings of both length and orientation modelling into account, it appears that the chosen approach is indeed *suitable* to adequately reproduce the manifold aspects involved in the peripheral perception of line segment lengths and – with some restrictions – of line segment orientation as well. The model's convincing replication performance supports the *decomposition hypothesis* and gives rise to the assumption that we correctly identified the perception mechanisms involved in the assessment of line segments, namely the essential contribution of line segments' end point information. Furthermore, we successfully implemented these mechanisms in the simulation algorithms.

As already mentioned, peripheral processing should play an even more important role in simultaneous line segment comparison tasks. Here, not only the length of each segment must be assessed, but also the comparison has to be accomplished. This might often be greatly facilitated by peripherally assessing the relevant attributes of both the target and comparison line segments at the same time – memory involvement as explicitly required in sequential comparison would thus be reduced. The chosen free gaze scenario also allows us to re-assess the *decomposition hypothesis*, eye movements will provide essential hints towards its validity. The analysis and interpretation of eye movement should further facilitate the exploration of the other processing steps that determine the cognitive structure of visual comparison tasks and allow for the testing of the other hypotheses formulated in this respect – in particular regarding the existence of *holistic* and *analytic* visual processing strategies, depending on *discrimination* difficulty.

We will now address this simultaneous comparison in the second part of the investigations. We thereby hope to integrate many aspects of the findings from the previous chapters and to be able to adapt the already formalised modelling aspects into an extended model for the simulation of perception processes involved in simultaneous line segment comparison.

Chapter 9

Simultaneous Comparison – Similarity Effects in Line Segment Perception

Let us recall the intention of the procedural concept this thesis follows: The aim is to establish a series of logical steps, each of which represents a valuable contribution to the overall understanding of visual processing of line segments in comparison scenarios. The empirical findings will then be formalised within a mathematical model.

Some of this "programme" has been completed in the previous chapters: The collection of relevant empirical data and their interpretation with regard to the contribution of *peripheral perception* processes and *decomposition* mechanisms to the overall understanding of line segment assessment has been accomplished. Furthermore, the formal representation of fundamental perception principles in this respect could successfully be implemented in a simulation model.

As introduced in Chapter 3, the investigation now moves on to studying line segment perception in a more complex scenario. The focus will be on *similarity effects* in line segment perception in *simultaneous comparison*. Furthermore, the intention will be pursued to integrate the previous findings into a comprehensive explanatory approach and to implement a computational model that adequately describes line segment perception and closely follows the *cognitive structure* of visual comparison tasks. When we consider that the implementation for the modelling of eccentricity effects – which we also render essential for non-peripheral line segment assessment – scored higher for the assessment of line segment length than orientation, it appears to be logical that the following experiments will be mainly concerned with line segment *length* rather than orientation aspects.

A wide range of potentially interesting issues can be investigated based on an experimental setting where two line segments are simultaneously presented side by side (see Figure 3.6). Opposed to the *eccentricity effects* in sequential comparison, *similarity effects* present such an issue in simultaneous comparison, for example. As motivated in Chapters 2 and 3, the following two experiments will be conducted:

- Experiment S1: The basis – Dynamic adjustment in length matching
- Experiment S2: Holistic vs. analytic processing – Binary judgements in length discrimination

Let us remember the basic hypotheses formulated in Section 2.4 and elaborate them in more detail.

The proposed discrimination task in Experiment S2 ("Which of the two line segments is the longer one?") implicitly suggests a variation of the discrimination difficulty, i.e. the length similarity of the two line segments shown simultaneously. The distinction between an *"easy"* and a *"difficult" discrimination task* should be particularly promising with respect to the applied *solution* strategies and should be reflected in corresponding *visual processing* strategies. Solving an easy discrimination task could be accomplished *"holistically"* without much focused information acquisition whereas the difficult condition might require an *"analytic"* processing mode. These two opposing solution strategies (*cognitive level*) will most likely result in different visual processing strategies (*perceptual level*), manifested in distinct differences in eye-movement parameters (*sensorimotor level*) and gaze trajectories.

For *high similarity comparisons ("difficult")*, i.e. when the two line segments' lengths are approximately, but not exactly equal, a *thorough visual analysis* of the scene must be expected. It is reasonable that overt shifts of attention occur not only between the two stimuli for the actual comparison, but that relevant features within the line segments are foveally scanned as well. Again, the *end points* of the line segments could be promising candidates for fixations if we assume that *"visually measuring"* the distance between two such points yields the required accurate length information. This data might then be stored in the respective *mental line segment model* to be compared with the comparison stimulus. However, even in high similarity conditions, subjects might apply *efficient* visual scanning strategies. These could constitute gaze trajectories that demonstrate an explicit fixation of only one of a line segment's end points and the *peripheral* assessment of the other. It is also possible that *intermediate* points "on" the line segment are fixated, such as its mid point ("center of gravity"), and that the overall length is subsequently *extrapolated* therefrom.

In case of *low similarity comparisons ("easy")*, i.e. when the line segments' lengths clearly differ, we would generally not expect such analytic visual scanning. Instead, we hypothesise that a *holistic* scene perception strategy yields sufficient information to make a correct decision as to which of the line segments is longer: A central point in between the two stimuli is fixated and the line segments' lengths are assessed *peripherally.* Rather than fixating such a central point, it might alternatively be favourable to *foveally* view one of the segments and *peripherally* assess the other. Finally, it might be feasible in some cases, even for apparently easy comparisons, to fixate both stimuli once or even to "switch" to *analytic "mode"*. These strategies could be pursued, for example, when different orientations of the two line segments induce (subjective) changes in perceived length due to *optical illusion effects.*

As also already motivated in Chapter 3, the binary judgement task in Experiment S2 does not only allow for the investigation of similarity effects in simultaneous length assessment that constitute potentially different processing strategies. Moreover, this experimental setting and the method of constant stimuli create ideal conditions for an eye-movement investigation. Rather than the dynamic adjustment of line segment length to match the target and comparison stimuli, the simple binary decision required here makes it easier to attribute particular shifts of attention uniquely to either adaptation processes or to an influence of specific stimulus attributes. The elimination of the dynamic process of line segment length adjustment should facilitate the monitoring and understanding of *comparison processes* and the influence of line segments attributes thereupon. This static procedure should in particular be beneficial for the interpretation of eye-movement patterns and associated *attention* and *memorisation/representation* processes.

However, it is absolutely essential to conduct Experiment S1 as well. Although we just motivated that dynamic processes certainly do not facilitate the interpretation of eye-movement data, the challenge to do so persists. Furthermore, a dynamic setting presents the attractive opportunity not only to learn about how these dynamic processes influence eye movements and vice versa, but also to include them into an enhanced model that simulates both eye movements/gaze trajectories and the relevant psychophysical data.

For a start, Experiment S1 is indispensable in establishing appropriate definitions for the easy and difficult conditions of Experiment S2. The results obtained will provide information on how accurately subjects can match the length of two line segments. We can then use this data to infer which differences between line segment lengths are difficult to distinguish – obviously those that lie within this accuracy – and which are easy to distinguish – those that lie considerably outside the accuracy. This distinction thus determines the easy and difficult conditions to be compared in Experiment S2.

The following section describes the algorithmic generation of the stimuli for the Experiments S1 and S2 and motivates the choice of levels for the independent variables in

- Experiment S1:
  - Length
  - Orientation
- Experiment S2:
  - Similarity level (i.e. "difficulty")
  - Length
  - Orientation

9.1 Variables and Stimuli

Let us again first consider the choice of independent variables and their respective different levels which will be varied in Experiments S1 and S2.

9.1.1 Levels of Independent Variables

One of the aims of Experiment S1 is to provide data that will subsequently be used to determine the experimental conditions in Experiment S2. When subjects adjust the length of the comparison line segments to match the perceived length of the target line segment, the adjustment will certainly incorporate some error. This error in Experiment S1 provides information regarding the magnitude of length differences between the target and comparison line segments that should be observed to constitute easy and difficult comparison conditions in Experiment S2. Due to these strong inter-experiment links, it must be ensured that the independent variables and their respective levels represent logical choices that can be maintained in both experiments in order to obtain reliable findings. The close resemblance of the two experimental settings should not render this too difficult, however. But, which would now be the most sensible choices for the levels of target line segment length and orientation?

For the length of the target line segments, we suggest three different magnitudes. In analogy to the previously chosen lengths in Experiment E1, it appears to be appropriate to choose "short", "intermediate" and "long" line segments whose lengths can either be perceived foveally or require parafoveal or peripheral processing, respectively. In fact, we initially motivated the choice of target length in Experiment E1 with the special requirements of Experiments S1 and S2. In a comparison scenario with unrestricted eye gaze, shifts of visual attention within one stimulus are then likely to be performed for "longer" line segments in order to foveally acquire relevant dimension information. We expect this to be true in particular in the difficult discrimination tasks of Experiment S2. Such a visual strategy would then support the assumed analytic processing hypothesis. The choice of target lengths in analogy to those studied in Experiment E1 also appears desirable – if not essential – in order to incorporate the conclusions from the eccentricity Experiments E0–E2 into the explanation of the observations in the similarity Experiments S1 and S2.

In Experiment E1 we had to realise that, due to the size of the eccentricity regions I–IV, the line segment lengths were limited and could not exactly be chosen according to the "standard" definitions of the eccentricity regions. Due to the restriction to "fit" the "long" line segment into eccentricity region I without overlap of other eccentricity regions in Experiment E1, "short", "intermediate" and "long" length had to be chosen as $1^o \pm 0.3^o$, $4^o \pm 0.3^o$ and $7^o \pm 0.3^o$, respectively. As no such restrictions apply in the current Experiments S1 and S2, the target line lengths here will more closely resemble the "classical" eccentricity categorisations, established in several studies (e.g. Tsal, 1983; Wright & Ward, 1994; Posner, 1980; Matlin & Foley, 1997): Foveal $\leq 3^o$, parafoveal $\leq 9^o$, peripheral $\geq 10^o$ (for details, see Sections 2.2 and 4.1). Thus, the following selection of target line segment lengths that will be presented in the Experiments S1 and S2 seems appropriate:

- Short: $1^o \pm 0.5^o$
- Intermediate: $6^o \pm 0.5^o$
- Long: $11^o \pm 0.5^o$

This choice accounts for equal distances between the different line segment lengths as well as attempts to minimise habitual effects that might occur when always exactly the same values have to be assessed. As before, "noise" is introduced that randomly varies the line segment length, here within a 0.5^o-band, around the short, intermediate and long target length levels.

With the systematic variation of the second independent variable in the Experiments S1 and S2, the orientation of the target line segment, a new aspect known to often significantly influence visual perception is added to the scope of the present investigation, namely that of *visual illusory effects*. More specifically, the "horizontal-vertical illusion" (see, e g., Künnapas, 1955; Piaget, 1969; and, more recently, Prinzmetal & Gettleman, 1993; Bartolomeo & Chokron, 2001) is of central interest here. As discussed in detail in Section 2.2, vertical or oblique line segments are generally perceived to be longer than horizontal ones that are displayed simultaneously and have identical physical length (see Figure 2.6).

In the present investigation, the inter-stimulus orientation and its possible illusory effects on the assessment of line segments' lengths must not be neglected. It should significantly influence the length assessment accuracy in Experiment S1 and will thus affect the determination of the easy and difficult discrimination conditions in Experiment S2. The present studies allow for the quantification of the horizontal-vertical illusion effect (Experiment S1) and they also present the opportunity to gain some insight into the underlying visual processes, manifested in eye movements. Their analysis (Experiment S1 and, in particular, Experiment S2) could help to explain the misjudgement and might finally lead to a better understanding not only of "normal" line segment length perception, but also of (at least this type of) visual illusions.

With the comparison line segment always being horizontally oriented, the following levels are chosen for the factor target line segment orientation:

- Horizontal: 0^o
- Oblique: 45^o
- Vertical: 90^o

This choice is made in accordance with that of the eccentricity Experiments E1 and E2. However, as orientation is not assessed in the following experiments, orientation "noise" to eliminate habituation effects does not have to be introduced here. The orientations of the target line segments will remain fixed at exactly 0, 45 or 90 degrees.

As for the third independent variable, the discrimination difficulty or, in other words, the length similarity of the target and comparison line segment – only varied in Experiment S2 – the choice of the exact parameters for either

- *easy discrimination*, i.e. *low similarity*, or
- *difficult discrimination*, i.e. *high similarity*,

depends on the results of Experiment S1 and will be discussed in the "Methods" section of Experiment S2 (see Section 11.2).

After the quantification of all relevant variables and the discussion of constraints that an appropriate stimulus design has to comply with, these stimuli can now be generated algorithmically.

9.1.2 Algorithmic Generation of Stimuli

Again, the stimulus line segments displayed in the Experiments S1 and S2 are pseudo-randomly generated. However, as the stimuli always appear at the same locations on the screen with a constant distance between them, the algorithmic generation of stimuli mainly consists of the determination of a list of all possible combinations of the independent variables.

With the independent variables target line segment length (short, intermediate and long) and target line segment orientation (horizontal, oblique and vertical) set as discussed

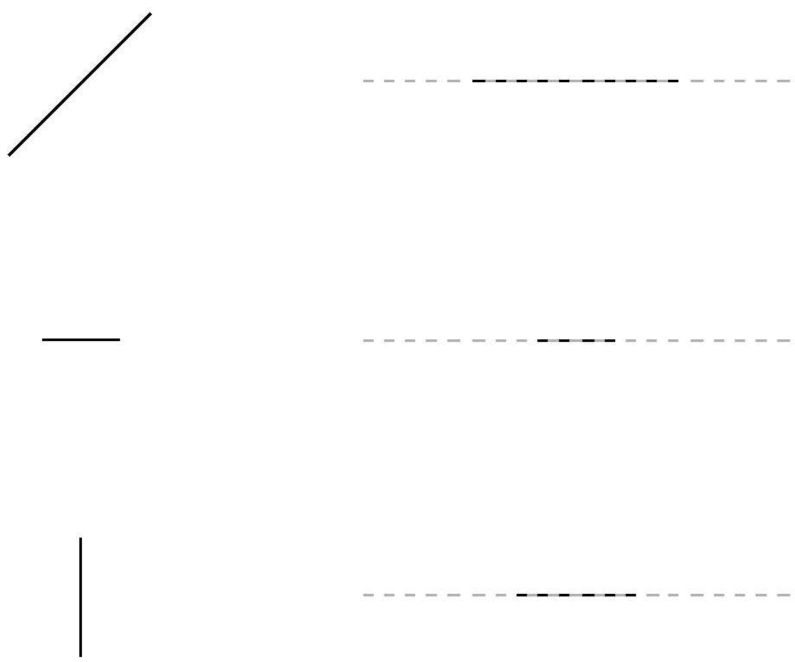


Figure 9.1: Three sample stimulus combinations in Experiment S1. Target line segments are shown on the left, comparisons on the right. Target stimuli here are oblique/long (top), horizontal/short (middle) and vertical/intermediate (bottom). The dotted lines mark the ranges for dynamic adjustment of the comparison line segments.

in the previous section, Figure 9.1 shows three algorithmically generated sample stimulus combinations as shown to subjects in Experiment S1. Subjects have to dynamically adjust the length of the (always horizontally oriented) comparison line segment to match the target length. Each subject will have to assess and adjust the length of a total of 90 line segments, so that every combination of the two factors will be displayed $90/(3 \cdot 3) = 10$ times. As we argued in the Experiments E1 and E2, this repetition factor should yield very reliable data for a statistical analysis while maintaining an acceptable experiment duration for subjects. Although considerably fewer trials have to be completed than in the eccentricity experiments, the average experiment duration still measured approximately 30 minutes: The more complex comparison task in combination with the dynamic adjustment procedure resulted in prolonged reaction times.

In the following chapter Experiment S1 investigates the assessment accuracy of line segment length in a simultaneous comparison setting. Using a dynamic method for comparison line segment adjustment, the findings allow us to draw conclusions about the *magnitude of the vertical-horizontal illusion* and to *establish the parameters for the discrimination difficulty levels easy and difficult* in Experiment S2. The chapter begins with an explanation of the method for this experiment, then the results will be presented and discussed in detail.

Chapter 10

Experiment S1: Simultaneous Dynamic Length Assessment

Experiment S1 is the first of two experiments that investigate the assessment and visual perception of specific stimulus dimensions – here, primarily line segment length – in the perceptually and cognitively more complex scenario of simultaneous comparison. It can be assumed, however, that the previously investigated effects of eccentric stimulus presentation on this stimulus dimension play an important role in simultaneous assessment as well. Results obtained in the Experiments E0–E2 should thus be viewed as valuable prerequisites for the understanding of the more complex processes in Experiments S1 and S2.

In Experiment S1, we explore the paradigm of simultaneous comparison paired with the psychophysical method of adjustment. On the one hand, this experimental design is required if we want to establish the *easy* and *difficult* conditions to investigate *holistic* and *analytic* visual processing strategies using the method of constant stimuli in the subsequent Experiment S2. The adjustment accuracies of the line segment lengths in Experiment S1 allow us to infer *which differences between line segment lengths are difficult to distinguish* – obviously those that lie within this accuracy – and which are easy to distinguish – those that lie considerably outside the accuracy – so that the discrimination/similarity conditions can be determined accordingly in Experiment S2. On the other hand, although we must accept that the dynamic adjustment does certainly not facilitate the interpretation of eye-movement data, the setting of Experiment S1 presents the attractive opportunity not only to learn about how these dynamic processes influence eye movements and vice versa, but also to include them into an enhanced model that simulates both eye movements/gaze trajectories and the relevant psychophysical data. Data recorded and analysed in this experiment will thus comprise psychophysical measures such as the reaction time RT, the adjusted length of the comparison line segment or its difference to the given target length. Furthermore, the relevant eye-movement data, such as number of fixations NF, fixation duration FD or saccade length SL (for details see Section 3.4.2) will be quantitatively analysed. The gaze trajectories will be qualitatively reviewed.

10.1 Method

10.1.1 Subjects

The subjects were fifteen experimentally naive students – ten male and five female – from the University of Bielefeld. Their average age was 27.5 years. All subjects had normal or corrected-to-normal vision and no pupil anomalies. The subjects were paid for their participation in the experiment.

10.1.2 Stimuli

The stimulus pictures were presented on a computer screen with a spatial resolution of 800×600 pixels ($39.0^o \times 29.4^o$ of visual angle). The stimuli consisted of two line segments that were placed on the screen so that their mid points were centered in the two respective hemifields of the display. The distance between the two line segments' mid points measured approximately 22^o. The target line segment consistently appeared on the left and showed one of the possible combinations of length and orientation as specified below. The comparison line segment was shown on the right, always in a horizontal orientation. Its initial length, i.e. that at the time of appearance, was randomly varied within the interval $[0.05^o, 2 \cdot \textit{target length}]$ with initial length being shorter or longer than the target length in 50% of the trials each. The initial comparison length could then be manipulated by mouse movements within the interval $[0.05^o, 2 \cdot \textit{target length}]$.

The line segments had a thickness of one pixel (0.05^o), an orientation of either 0^o ("horizontal"), 45^o ("oblique") or 90^o ("vertical") and a length of either $1^o \pm 0.5^o$ ("short"), $6^o \pm 0.5^o$ ("intermediate") or $11^o \pm 0.5^o$ ("long") of visual angle (see Section 9.1). The line segments and the background were set to the same dark and light grey colours, respectively, as in the Experiments E0–E2. Figure 10.1 shows a typical stimulus picture.

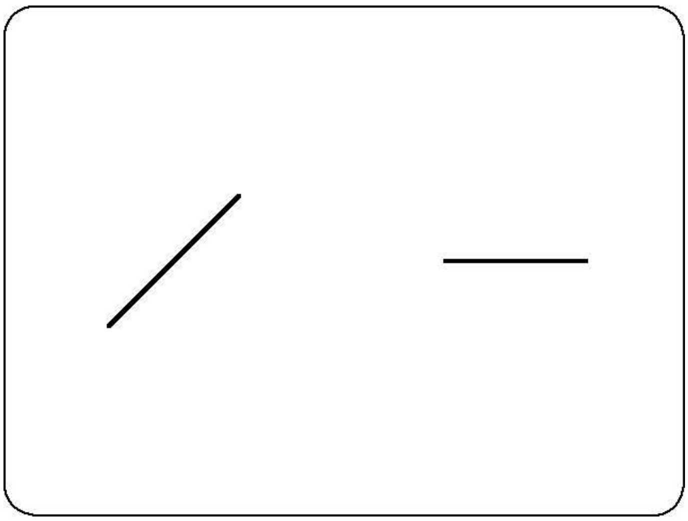


Figure 10.1: Typical stimulus picture in Experiment S1. Subjects had to adjust the length of the horizontal comparison line segment (right hemifield) so that it matched the perceived length of the target line segment displayed in the left hemifield.

10.1.3 Apparatus

The apparatus used was the same as in Experiment E0.

10.1.4 Procedure

All subjects were tested individually. Prior to the start of the experiment, they were provided with written instructions that explained their task. Next, the eye tracker was set up and calibrated for each subject. To complete the calibration procedure, subjects had to look at nine dots that successively appeared at specific locations on the display.

Each trial of the experiment started with the presentation of the fixation point at the center of the screen (Frame 1, see Figure 10.2). 700 ms after fixation point onset, the two line segments were displayed simultaneously in the left (target) and right (comparison) hemifields, respectively (Frame 2). The fixation point disappeared 200 ms thereafter. The instructions required the subjects to assess the length of the target line segment and to adjust the length of the comparison line segment accordingly as accurately as possible. Subjects accomplished the length adjustment by horizontal mouse movements that were synchronised with the stimulus display (Frame 3). Moving the mouse to the right resulted in an elongation of the comparison line segment, movements to the left in a shortening. The resolution for the adjustment was 0.1^o (equivalent to two pixels). Mouse movements resulted in a symmetric change (relative to the mid point) of the length of the comparison line segment. The length was increased or decreased by 0.05^o, i.e. in one-pixel increments or decrements, at each end of the line segment. When subjects had finished their adjustment, they pressed the left mouse button for confirmation and the next trial started.

As mentioned above, the comparison line segment was always shown on the right, intuitively corresponding with the (right) hand that usually operates the computer mouse.

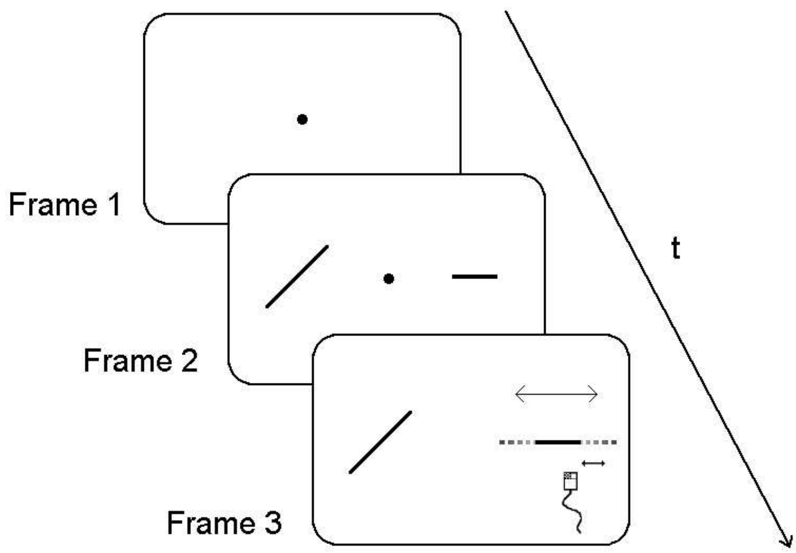


Figure 10.2: The sequence of procedural steps for a trial of Experiment S1. Frame 1: Fixation point. Frame 2: Simultaneous display of target and comparison line segments. Frame 3: Adjustment of comparison line segment length.

Changing the presentation hemifields for the two stimuli would have resulted in initial mouse movements in order to identify the comparison line segment. These are certainly unrelated to the actual task and would have rendered data analysis more difficult and influenced the subjects' performance. Similar effects could have been expected if the comparison line segment had been shown in changing rather than a constant (here: Horizontal) orientation.

No gaze restrictions applied throughout Experiment S1 and subjects could move their gaze freely across the whole screen. Figure 10.2 illustrates the sequence of procedural steps for one trial.

In order to compensate for the possible displacement of the headset due to head movements, the eye tracker was recalibrated after every 9 trials. In contrast to the eccentricity Experiments E0–E2 where tight gaze restrictions applied, minor misalignments of the headset can be tolerated now and would not lead to potentially unmotivated abortion of trials due to boundary violations.

Subjects viewed a total of 90 stimulus pictures during the experiment so that each possible combination of the three target lengths and the three target orientations was displayed ten times. Prior to the experimental trials, nine practice trials were conducted to accustom the subjects to the eye-tracker headset and the experimental task. As well as the reaction time and the assessment/adjustment accuracy, eye movements were monitored and written into a file. The recorded data contained all required information for the subsequent computation of the eye-movement parameters relevant here and for the visualisation of gaze trajectories that occurred during the dynamic length adjustment process.

10.2 Results

Rather than the eye movements recorded during the experimental trials, we will first address the "conventional" psychophysical data, namely the length assessment accuracy. It is manifested in the length deviation DL, i.e. the difference between the target line segment length and the adjusted length of the comparison line segment. On the one hand, this measure is of particular importance for Experiment S2, where DL and the associated standard deviation σ_{DL} determine the (then fixed) comparison line segment lengths for the easy and difficult discrimination conditions. On the other hand, the statistical analysis of DL allows us to once again establish and *quantify the visual illusory effects* – if present – induced by the orientation difference between the target and comparison line segments.

All experimental data is subjected to a two-factorial analysis of variance in order to account for the two independent variables target line segment length and orientation. The effects of these factors are tested on the dependent variables length deviation DL ("length assessment accuracy") and on the following eye-movement parameters (for detailed definitions, see Section 3.4): Number of fixations (NF), fixation duration (FD) and saccade length (SL) and derived measures such as number of successive fixations within the same hemifield (FW) or the number of saccades between hemifields (SB). In analogy to the eccentricity Experiments E0–E2, the reaction time RT are entered into an analysis of variance as well. The following section presents the detailed results for all dependent variables, starting with the analysis of RT.

10.2.1 Dependent Variables

Reaction Time RT

First, we chart the relative frequencies of the reaction time RT in a histogram (see Figure 10.3, left). The distribution is based on all measured values for RT, irrespective of target line segment length or orientation, and takes into account the data from all subjects. We measure a minimum RT of 429 ms and a maximum RT of 27151 ms, the overall mean is 4626 ms. The histogram reaches a peak at approximately 2900 ms. Approximately 95% of the values lie within the interval of 1800 to 8000 ms, the general shape of the distribution can be fitted by an asymmetrical function with positive skewness of +2.60.

The analysis of variance yields a significant main effect on RT for the factor target line segment length ($F(2; 28) = 18.25; p < 0.001$). When the target line segment is short subjects require 3841.6 ms on average to assess its length and adjust the comparison line segment accordingly. For intermediate target lengths (parafoveal), RT increases to 4581.4 ms, for long line segments (peripheral) to 5426.6 ms. A Newman-Keuls reveals that theses differences are indeed all significantly different from each other: ($R_{crit} = 590.132; p = 0.008$) for the comparison between short and intermediate target lengths, ($R_{crit} = 660.938; p < 0.001$) for short vs. long target lengths and ($R_{crit} = 609.419; p = 0.004$) for intermediate vs. long target lengths. The factor target line segment orientation does not exert a significant effect on RT ($F(2; 28) = 0.54; p = 0.588$).

A closer inspection of the data, however, yields an interaction effect between target length and orientation ($F(2; 56) = 3.11; p < 0.022$). When targets are short, RT decreases depending on their orientation: Horizontally oriented target line segments take longer (4158.1 ms) to assess than oblique ones (3806.8 ms), which again take longer to assess than vertical ones (3530.6 ms). The post-hoc comparison of means using a Newman-

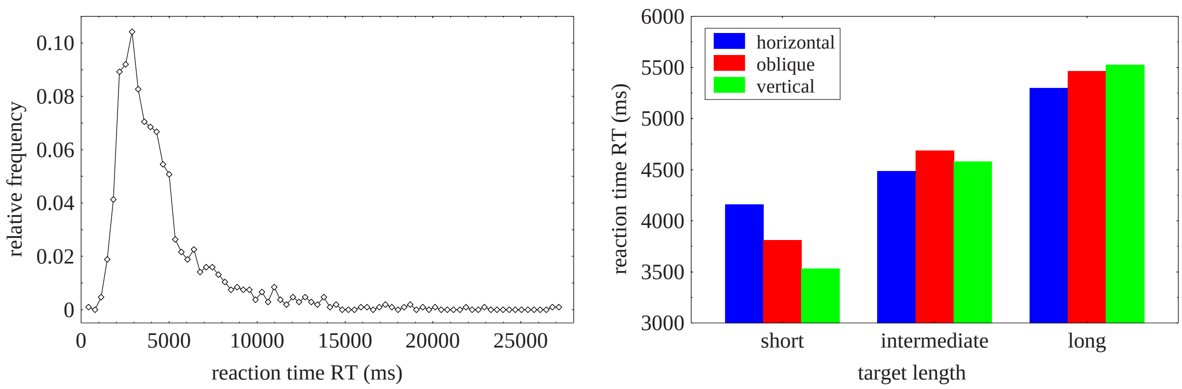


Figure 10.3: Left: Cumulative relative frequency distribution of reaction times RT over all target line segment length and orientation levels for all subjects. Right: Reaction time RT as a function of target line segment length, separated for the three target orientations.

Keuls test confirms the existence of significant differences between the three orientation levels for short line segments: ($R_{crit} = 630.640; p = 0.044$) for the comparison between horizontal and oblique target orientations and ($R_{crit} = 642.835; p = 0.004$) for horizontal vs. vertical target orientations. However, the comparison between short oblique and short vertical targets does not produce significant differences in RT, but only a tendency ($R_{crit} = 500.908; p = 0.104$). For intermediate and, in particular, for long target line segments this dependence cannot be found (qualitatively visible in Figure 10.3, right). RT for these lengths remains almost constant irrespective of the factor orientation, only for long target line segments there appears to be an inverse tendency to that found for short line segments: RT slightly increases from horizontally through oblique to vertically oriented target line segments. Here, Newman-Keuls tests confirm that no significant differences exist between the three orientation levels for intermediate or long targets. Intermediate targets: ($R_{crit} = 461.318; p = 0.616$) for the comparison between horizontal and oblique target orientations, ($R_{crit} = 440.567; p = 0.632$) for horizontal vs. vertical and ($R_{crit} = 430.450; p = 0.647$) for oblique vs. vertical. Long targets: ($R_{crit} = 560.716; p = 0.407$) for the comparison between horizontal and oblique target orientations, ($R_{crit} = 550.349; p = 0.480$) for horizontal vs. vertical and ($R_{crit} = 395.978; p = 0.745$) for oblique vs. vertical. Figure 10.3 (right) shows RT as a function of target line segment length and orientation.

Length Deviation DL

In contrast to the separate analyses of the length deviations for either absolute (DL_p) or "directional" (DL) cases, we only consider DL in the present experiment. This appears to be sensible for various reasons. First, we must keep in mind that the length deviations – and their respective standard deviations – observed in this experiment will be used to determine the lengths of the comparison line segments in Experiment S2. As we intend to create easy and difficult discrimination conditions, the lengths should guarantee that target and comparison line segment lengths are indeed quite similar or rather different in length, respectively. This certainly requires considering length deviations that take into account the "direction" of the deviation, i.e. whether the length of the target line segment was under- or overestimated. The second reason for preferring the analysis of DL over that of DL_p is closely related to the over- and underestimation aspect. We not only intend to establish the discrimination conditions for the subsequent experiment, but are also interested in the investigation of the magnitude and "direction" of the visual illusory effect on the perceived lengths, induced by the specific alignment of the two stimulus constituents. Furthermore, with a view to the development of a comprehensive model that not only simulates certain aspects of the visual "behaviour", but also correctly represents the adjustment procedure and the illusion-induced effects, the analysis of the directional deviation DL of the comparison line segment length from the target line segment length is recommended.

DL will be negative in case the length of the comparison line segment is shorter than that of the target ("target underestimation"), and positive otherwise ("target overestimation"). DL is again a relative measure that correlates the deviation to the target length as defined in Equation 6.1 in Section 6.2. Example: A comparison line segment that is adjusted to 90 pixels when the target is 100 pixels long constitutes a length deviation of $(90 - 100)/100 = -0.1$, i.e. an underestimation of the target length of (-)10%.

In order to test the effects of the target line segment length and orientation on DL, a two-way analysis of variance is conducted first. The analysis yields significant main effects on DL for both factors. Significance levels are computed as $(F(2;28) = 53.10; p < 0.001)$ for target line segment length and as $(F(2;28) = 10.87; p < 0.001)$ for target line segment orientation. In general, target line segment lengths are overestimated. This overestimation is significantly more pronounced the shorter the target line segments are. When data is averaged over the target orientations (for all subjects), comparison line segment lengths deviate from the target lengths by 15.3% for short target lengths, 10.4% for intermediate target lengths and 7.0% for long target lengths. A Newman-Keuls test again confirms that these means are all significantly different from each other: $(R_{crit} = 0.025; p = 0.009)$ for the comparison between short and intermediate target lengths, $(R_{crit} = 0.026; p < 0.001)$ for short vs. long target lengths and $(R_{crit} = 0.023; p = 0.038)$ for intermediate vs. long target lengths.

With respect to the target orientation, the analysis shows that oblique and vertical target line segments are significantly more overestimated than those that are horizontally oriented. The cumulation of data over the factor target line segment length yields that subjects overestimate the lengths of the target line segments by 4.8% (horizontal), 14.4% (oblique) and 13.4% (vertical) on average, i.e. the lengths of the comparison line segments are adjusted longer than the physical target lengths. A Newman-Keuls test confirms that only the means for the comparisons between horizontal and oblique targets $(R_{crit} = 0.026; p < 0.001)$ and between horizontal and vertical targets $(R_{crit} = 0.026; p < 0.001)$ are significantly different. The comparison between oblique and

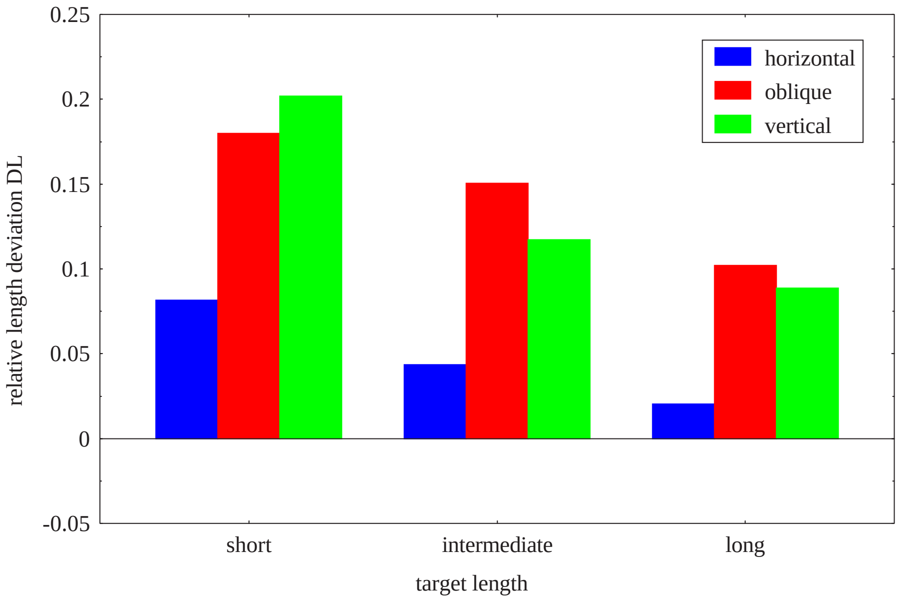


Figure 10.4: Length deviation DL as a function of target line segment length, separated for the three target orientations.

vertical targets does not not produce a significant difference ($R_{crit} = 0.021; p = 0.301$). In addition, the interaction between target line segment length and orientation reaches significance ($F(4; 56) = 5.06; p = 0.001$). Figure 10.4 shows the relative length deviation DL as a function of target line segment length and orientation.

As both the factors target line segment length and orientation as well as their interaction exert a significant effect on the length deviation DL, it will apparently be necessary to individually set the lengths of the comparison line segments in Experiment S2 for the combinations of the two factors later on. Therefore, all relevant data is summarised in Table 10.1. The upper two rows of each “block” of the table chart the adjusted lengths of the comparison line segments LC and the associated standard deviations σ_{LC} for all factor combinations of target line segment length and orientation in Experiment S1. The lower two rows contain in addition the derived relative length deviations DL of the comparison from the target line segments lengths and their respective standard deviations σ_{DL} upon which the previous analyses in this section were based. These measures will subsequently be used in Experiment S2 to determine the comparison line segment lengths for the binary comparison task (see Sections 11.1 and 11.2).

After the analyses yielded significant effects of the factors target line segment length and orientation on the “conventional” empirical data types reaction time RT and length deviation DL, these effects will be tested on ”typical” eye-movement parameters in the following paragraphs. The integration of all results in the subsequent discussion might then facilitate the interpretation and understanding of the observations and underlying perception principles.

target orientation		target length LT		
		short (1^o)	intermediate (6^o)	long (11^o)
	horizontal (0^o)	LC = 1.082^o	LC = 6.260^o	LC = 11.219^o
		$\sigma_{LC} = 0.131^o$	$\sigma_{LC} = 0.508^o$	$\sigma_{LC} = 0.632^o$
		⇓	⇓	⇓
		DL = 0.082	DL = 0.044	DL = 0.020
		$\sigma_{DL} = 0.131$	$\sigma_{DL} = 0.084$	$\sigma_{DL} = 0.057$
	oblique (45^o)	LC = 1.127^o	LC = 6.896^o	LC = 12.090^o
		$\sigma_{LC} = 0.132^o$	$\sigma_{LC} = 0.611^o$	$\sigma_{LC} = 0.901^o$
		⇓	⇓	⇓
		DL = 0.18	DL = 0.151	DL = 0.102
		$\sigma_{DL} = 0.132$	$\sigma_{DL} = 0.102$	$\sigma_{DL} = 0.081$
	vertical (90^o)	LC = 1.202^o	LC = 6.698^o	LC = 11.949^o
		$\sigma_{LC} = 0.123^o$	$\sigma_{LC} = 0.638^o$	$\sigma_{LC} = 0.969^o$
		⇓	⇓	⇓
		DL = 0.202	DL = 0.117	DL = 0.089
		$\sigma_{DL} = 0.123$	$\sigma_{DL} = 0.106$	$\sigma_{DL} = 0.087$

Table 10.1: Overview of adjusted lengths of the comparison line segments LC, length deviations DL of the comparison from the target line segments and the respective standard deviations σ_{LC} and σ_{DL} for all combinations of target line segment lengths LT and orientations in Experiment S1.

Analysis of Eye-Movement Data: Preliminaries

One of the most fundamental eye-movement parameters to be investigated in a statistical analysis is certainly the number of fixations NF that subjects perform during an experimental trial. Whereas the overall number of fixations in general yields valuable information on the task complexity and the influence of certain experimental conditions on visual perception and, furthermore, cognitive processes, the analysis of spatially separate fixations is often even more rewarding. This appears to be the case in this experiment also, where *local* numbers of fixations will be considered. Here, these local NFs will be computed for the two stimulus hemifields, i.e. for fixations that lie in proximity to the presentation positions of the target and the comparison line segment, respectively.

Such a distinction seems to be sensible here if we consider the overall distribution of the fixations. In order to get a better impression of this distribution, the fixation points are superimposed onto the stimulus display as presented in Figures 10.5 and 10.6. Figure 10.5 shows the distribution of the fixation points of all subjects when a long target stimulus is in an oblique orientation, Figure 10.6 illustrates the distributions for all possible combinations of target line segment lengths and orientations. Qualitatively, the figures already confirm that indeed the majority of the fixations lies within a certain range around the two line segments. However, "intermittent" fixations must not be discarded as

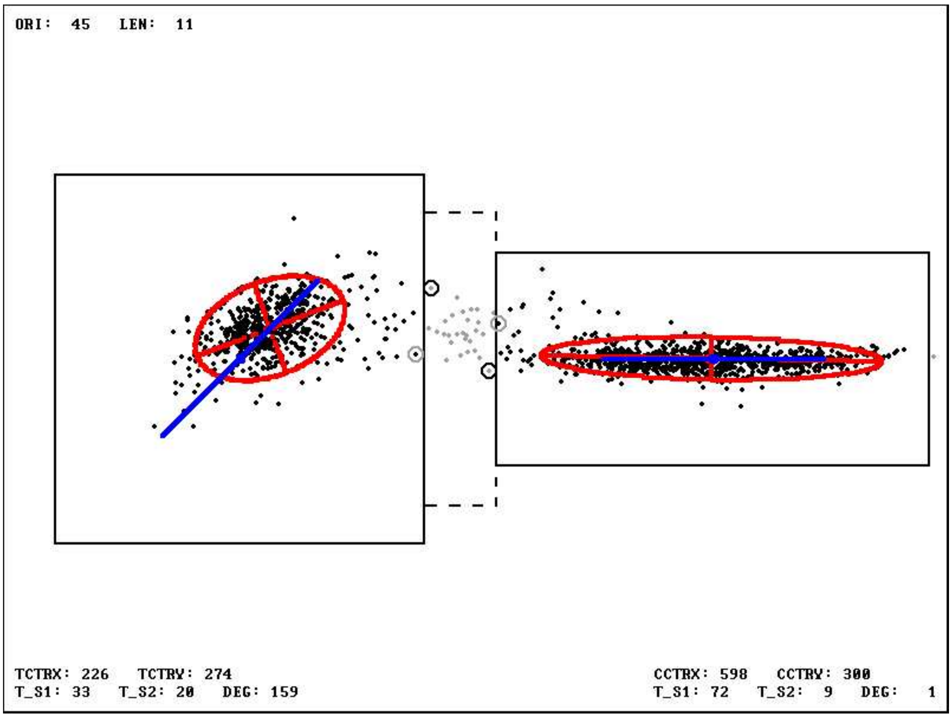


Figure 10.5: Distribution of the fixation points for a long target stimulus in an oblique orientation, aggregated over all subjects. The length of the comparison line segment equals that of the target. The stimuli line segments are coloured blue, the blue dots mark the segments' centers. The black boxes circumscribe the stimuli so that a minimum distance of 5^o is maintained between the box edges and the enclosed stimuli. A PCA yields the red ellipses. The black dotted box circumscribes the intermittent section.

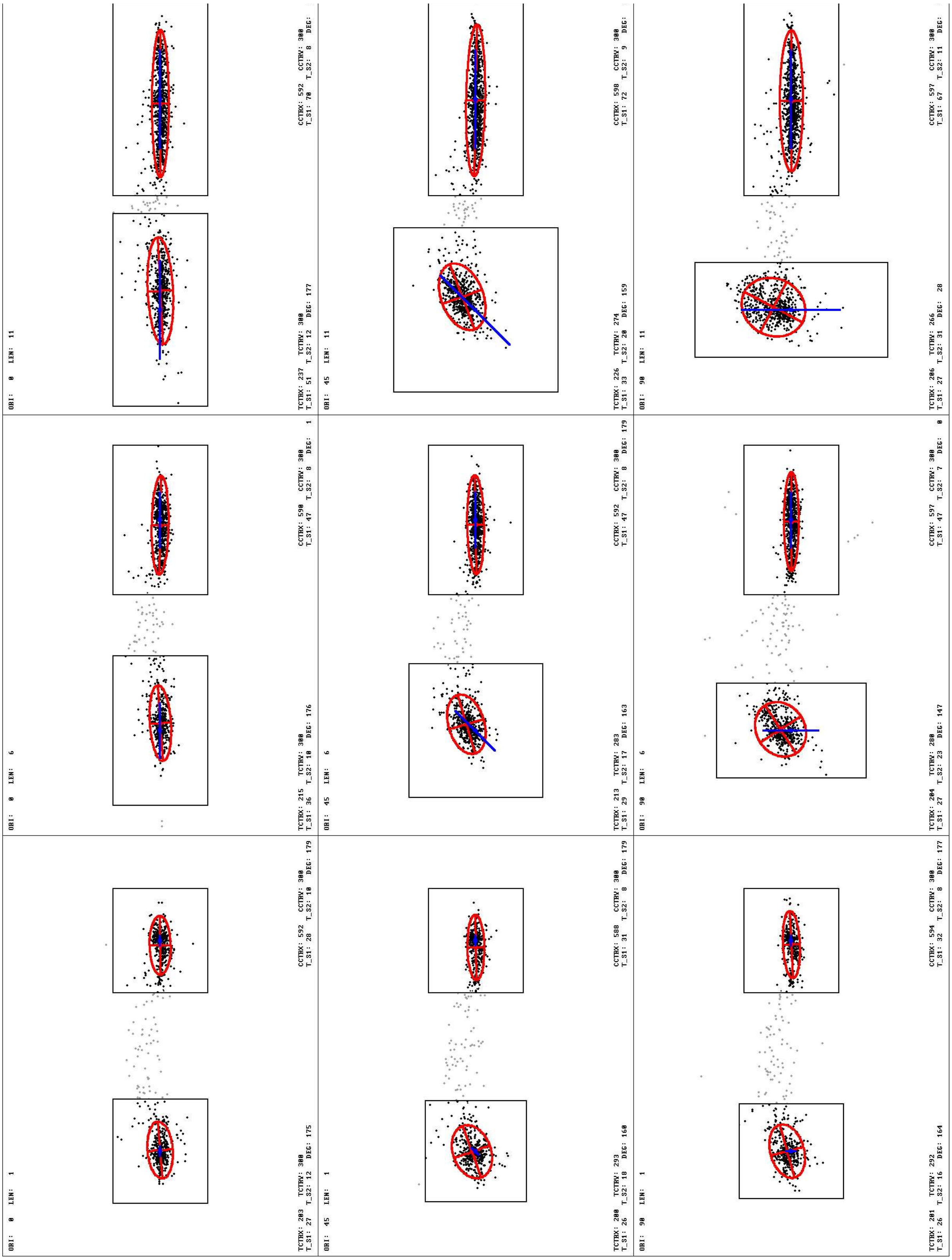


Figure 10.6: Distribution of the fixation points for all possible combinations of target line segment lengths and orientations, aggregated over all subjects (analogous to Figure 10.5).

they yield information on peripheral visual processing. Thus, rather than only considering the two stimulus display hemifields, we divide the space into two sections surrounding the line segments *and* an intermittent section for which separate analyses for NF and, in the following paragraphs, for various other eye-movement parameters will be computed.

The size of the stimulus sections is individually calculated according to the respective stimulus dimensions so that a minimum distance of 5^o – relative to the outermost points of the stimuli – is observed. This measure is established to ensure that only fixations are included in the analyses that can be characterised at least "near foveal" (to the respective stimulus) whereas the intermittent section contains fixations that allow for the peripheral perception of the target and/or comparison stimuli. Furthermore, this choice conveniently excludes fixation artifacts from the analysis that obviously do not contribute to the assessment task. The intermittent section's width fills up the space between the stimulus sections, its height is computed to the mean of the heights of the two stimulus sections.

In order to validate this – seemingly arbitrary – choice of the size of these three sections, a cluster analysis is computed using the *k-means clustering* algorithm (e.g. Hartigan & Wong, 1979). This non-hierarchial method initially takes the number of components of the population equal to the final required number k of clusters. In this step itself the final required number of clusters is chosen such that the points are mutually farthest apart. Next, it examines each component in the population and assigns it to one of the clusters depending on the *minimum distance*. The centroid's position is recalculated every time a component is added to the cluster. These steps are re-iterated until all components are grouped into the final required number of clusters and no data points have to be regrouped. When this terminates, all cluster centers are at the mean of their Voronoi sets, i.e. the set of data points which are nearest to the cluster center.

The comparison of the clustering (k-means algorithm with $k = 3$) and the definition of sections as described in the previous paragraph yields very little divergence, only few fixations are assigned to different clusters or sections, respectively. On average, this ratio of inconsistently assigned fixations measures only 0.4%[1]. This then indicates that the "sectioning" defines a useful basis for the subsequent computation of local eye-movement parameters.

It could, however, be argued that the different sizes of the sections that contain the relevant data bias the analyses and possibly produce misleading results and lead to incorrect conclusions. Such effects could emerge either when comparing results for different line segment lengths, between target and comparison stimuli sections for oblique target line segments, or for the comparison between oblique and horizontal or vertical target line segments. However, the Figures 10.5 and 10.6 qualitatively demonstrate that indeed all relevant fixations lie within the marked sections, irrespective of their size. This again confirms the sensible choice of these sections and, furthermore, discourages the argument of a possible size interaction. It can thus be assumed that no such influence or bias must

[1] In Figure 10.5, the encircled dots mark the inconsistently assigned fixations. Whereas the k-means algorithm assigned the two fixations surrounded by the grey circles to the intermittent section and the two fixations surrounded by black circles to the stimuli sections, the box boundaries suggest the opposite.

be feared or would require compensation in the statistical analyses. For clarity reasons Figures 10.5 and 10.6 only visualise the boundaries of the stimulus sections (black boxes). The red ellipses also included in the figure will be discussed later in this chapter (see Section 10.3).

Number of Fixations NF

After the definitions and the evaluation of the boundaries for eye-movement data to be taken into account for the subsequent analyses, we thus define three separate measures for the numbers of fixations accordingly: NF_T and NF_C for fixations that occur in proximity to the target and the comparison stimuli, respectively, and NF_I for intermittent fixations that occur between the two stimuli. To start with, a separate analysis of the overall number of fixations NF is computed and possible effects of the independent variables target line segment length and orientation thereupon will be established.

The analysis of variance reveals a significant main effect of the factor target line segment length on NF ($F(2;28) = 24.29; p < 0.001$). On average, subjects fixate 8.46 times on the whole stimulus display during the assessment of a short target line segment. When the target line segment has intermediate length, the overall number of fixations NF increases to 11.63 and further to 14.81 fixations for long targets. These means are indeed all significantly different from each other as a Newman-Keuls test demonstrates: ($R_{crit} = 1.856; p = 0.002$) for the comparison between short and intermediate targets, ($R_{crit} = 2.264; p < 0.001$) for short vs. long targets and ($R_{crit} = 1.902; p = 0.002$) for intermediate vs. long targets.

In contrast, independent of the target orientation, NF remains almost constant at approximately 11.65 when data is aggregated over all target lengths. Accordingly, no significant effect on NF can be observed for the factor target line segment orientation ($F(2;28) = 0.92; p = 0.411$). The interaction between target line segment length and orientation does not reach significance either ($F(4;56) = 2.11; p = 0.112$). Figure 10.7 graphically illustrates these dependences and charts the relevant mean values for NF as a function of target line segment length and orientation.

In analogy to the statistical analyses for NF, similar analyses are computed for the local numbers of fixations NF_T, NF_C and NF_I. The analysis of variance for NF_T, i.e. the number of fixations that occur in proximity to the target line segment, yields a significant main effect for the factor target line segment length ($F(2;28) = 14.32; p < 0.001$), whereas no such significant main effect is established for the factor target line segment orientation ($F(2;28) = 1.45; p = 0.252$). In correspondence with these results, NF_T notably increases from only 3.83 fixations in the target area for short target line segments through 4.58 for intermediate to 5.65 for long targets. Approximately 4.65 fixations occur in the target area, independent of the target orientation, reflecting the lacking significant effect of target orientation on NF_T. These means are again all significantly different from each other as a Newman-Keuls test demonstrates: ($R_{crit} = 0.695; p = 0.039$) for the comparison between short and intermediate targets, ($R_{crit} = 0.846; p < 0.001$) for short vs. long targets and ($R_{crit} = 0.790; p = 0.004$) for intermediate vs. long targets. As was the case for NF, the

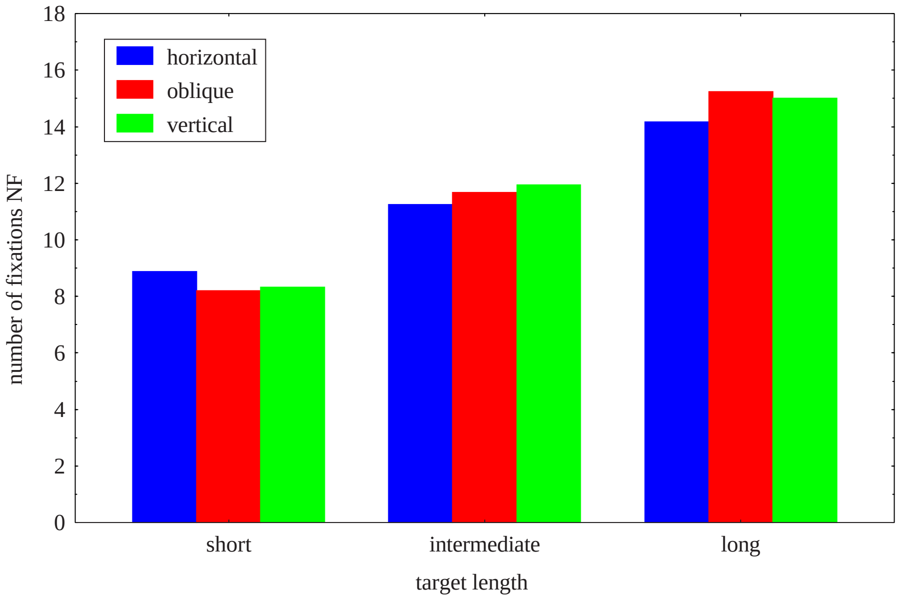


Figure 10.7: Overall number of fixations NF as a function of target line segment length, separated for the three target orientations.

interaction between target line segment length and orientation does not reach a significant level either ($F(4;56) = 1.24; p = 0.303$). Figure 10.8 (top left) visualises all means for NF_T for the three possible target orientations as a function of target length.

Similar effects of the factors target line segment length and orientation can be found on NF_C, i.e. the number of fixations that occur in proximity to the comparison line segment. Again, target length exerts a highly significant effect ($F(2;28) = 28.76; p < 0.001$), whereas target orientation does not ($F(2;28) = 1.16; p = 0.327$). As visible in Figure 10.8 (top right), NF_C remains almost identical at 6.4 fixations for all target orientations, but increases for longer target line segments. More specifically, averaged over the target orientations, NF_C is computed to 4.07 for short, to 6.54 for intermediate and to 8.86 for long target line segments. Yet again, these means are all significantly different from each other (according to a Newman-Keuls test): ($R_{crit} = 1.500; p < 0.001$) for the comparison between short and intermediate targets, ($R_{crit} = 1.576; p < 0.001$) for short vs. long targets and ($R_{crit} = 1.293; p = 0.001$) for intermediate vs. long targets. The interaction between target line segment length and orientation does not reach a significant level ($F(4;56) = 2.28; p = 0.101$).

The statistical analysis of the number of intermittent fixations NF_I that occur in the area between the two stimuli yields rather different results compared to those obtained in the previous analyses of the NFs. First, it must be noted that the main effects of the factors target line segment length ($F(2;28) = 9.72; p < 0.001$) and orientation ($F(2;28) = 12.32; p < 0.001$) both reach significance. Whereas NF, NF_T and NF_C remained almost unchanged for the different target orientations, NF_I significantly increases for oblique and vertical target orientations, compared to horizontals: 0.37 fixations for horizontal, 0.41 fixations for oblique and 0.59 fixations for vertical target line segments. A post-hoc comparison of means (Newman-Keuls test) shows that the following means are significantly different from each other: ($R_{crit} = 0.113; p < 0.001$) for the comparison between horizontal and vertical targets and ($R_{crit} = 0.110; p = 0.001$) for oblique vs. vertical targets. The comparison of means between horizontal and oblique targets does not produce a significant effect ($R_{crit} = 0.092; p = 0.397$).

Furthermore, complementary to the means computed for NF, NF_T and NF_C, NF_I now *de*creases from 0.57 fixations for short to 0.51 fixations for intermediate and then to 0.29 fixations for long target line segments. A post-hoc comparison of means (Newman-Keuls test) shows that the following means are significantly different from each other: ($R_{crit} = 0.163; p = 0.001$) for the comparison between short and long targets and ($R_{crit} = 0.159; p = 0.002$) for intermediate vs. long targets. The comparison of means between short and intermediate targets does not produce a significant effect ($R_{crit} = 0.134; p = 0.449$). On average, intermittent fixations thus occur in between every second and third trial. In other words, only approximately 4% of all fixations fall into the intermittent section. The interaction between target line segment length and orientation does not reach significance level ($F(4; 56) = 1.47; p = 0.131$). Figure 10.8 (bottom left) charts the mean NF_I for the possible factor combinations.

Considering the absolute values of NF_T, NF_C and NF_I it can be suspected that signif-

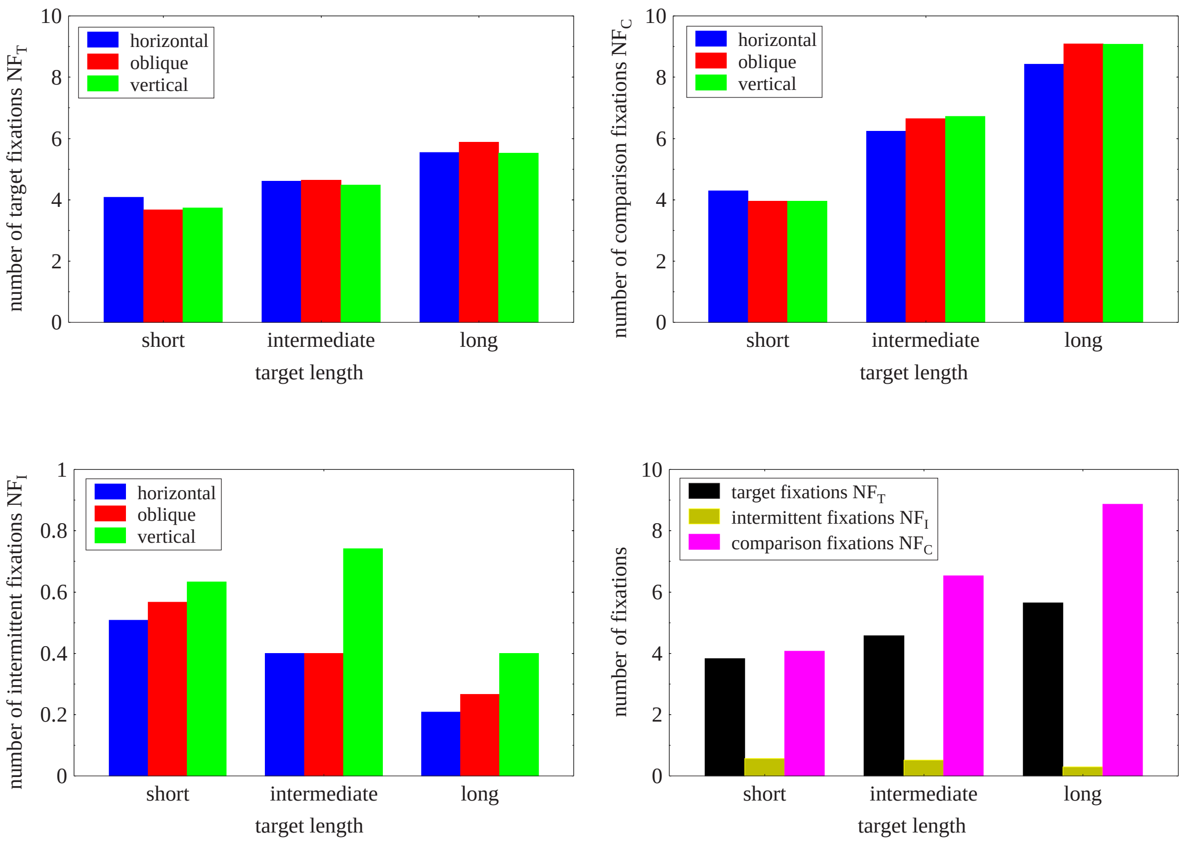


Figure 10.8: Local numbers of fixations in the target (NF_T, top left), the comparison (NF_C, top right) and the intermittent (NF_I, bottom left) sections as a function of target line segment length and orientation. Bottom right: Comparison of the local numbers of fixations in the target (NF_T), intermittent (NF_I) and comparison (NF_C) sections as a function of target line segment length. (N.B.: Different vertical scale used for NF_I)

icant differences exist between those measures. To validate this dependence, an enhanced analysis of variance is computed. It tests in particular for the effects of the additional factor “section” on the number of fixations with factor levels being the target, comparison and intermittent fixation sections. Indeed, the analysis confirms the assumed significant effect of the fixation section on the number of fixations ($F(2; 28) = 49.02; p < 0.001$). Furthermore, a post-hoc comparison of means using the Newman-Keuls test is computed. It reveals that significant differences not only exist between NF_T and NF_I ($R_{crit} = 0.931; p < 0.001$) and between NF_C and NF_I ($R_{crit} = 1.814; p < 0.001$), but also between NF_T and NF_C ($R_{crit} = 1.119; p = 0.004$). As the separate anlyses for NF_T and NF_C suggested already, considerably fewer fixations occur in the target (4.69) than in the comparison section (6.49), almost none (0.46) in the intermittent section. These statistically significant differences are visualised in Figure 10.8 (bottom right) where NF_T, NF_C and NF_I are displayed in direct comparison for the three possible target lengths.

In the following section, an eye-movement parameter directly associated with the number of fixations is considered, namely the mean fixation duration FD. In conjunction with NF, FD should yield valuable results for the discussion of the effects that the manipulation of stimuli determinants has on the comparison and matching process and the overall distribution of visual attention.

Fixation Duration FD

Analogous to the analyses for the number of fixations, separate analyses for FD and the local fixation durations within the target section (FD_T), the comparison section (FD_C) and the intermittent section (FD_I) will be computed. Analyses of variance will establish the effects of the factors target line segment length and orientation on the FDs. Again, typical values of descriptive statistics such as FD means will be computed and visualised in bar charts.

With respect to the overall fixation duration FD, irrespective of any designated areas in the stimulus picture, the two-factorial analysis of variance reveals a significant main effect for the factor target length ($F(2; 28) = 17.26; p < 0.001$). The absolute means of FD indicate a decrease from 338.83 ms for short target line segments through 309.15 ms for intermediate down to 284.61 ms for long targets. Again, the target line segment orientation does not significantly influence FD ($F(2; 28) = 0.83; p = 0.447$). The average fixation duration only differs between 314.96 ms for vertical targets and 304.18 ms for oblique ones. When horizontal targets are presented, the mean FD is 313.35 ms. The interaction between target segment length and orientation does not reach significance either ($F(4; 56) = 0.56; p = 0.692$). Figure 10.9 charts the mean values for NF as a function of target line segment length and orientation.

In succession, analogous analyses are computed for the local fixation durations FD_T, FD_C and FD_I. Fixations in proximity to the target line segment location last 219.93 ms, 249.34 ms and 240.96 ms for short, intermediate and long targets, respectively. An analysis of variance demonstrates that the factor target line segment length has a significant effect on FD_T ($F(2; 28) = 15.24; p < 0.001$). However, as can be suspected from the differences

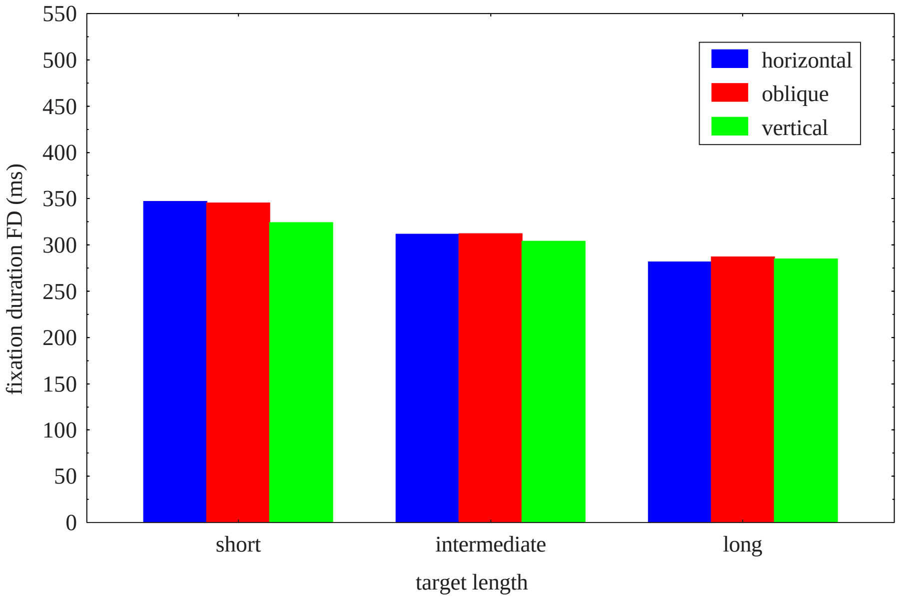


Figure 10.9: Average global fixation duration FD as a function of target line segment length, separated for the three target orientations.

between the means for the three target lengths, this effect originates from significant differences in FD_T between short and intermediate and between short and long target line segments only. The corresponding results of the Newman-Keuls test produced ($R_{crit} = 12.392; p < 0.001$) and ($R_{crit} = 14.911; p = 0.004$) for those two comparisons, but ($R_{crit} = 11.722; p = 0.149$), i.e. no significant effect, for the comparison between intermediate and long targets.

Testing the effects of the factor orientation on FD_T produces rather similar results. FD_T is computed to 240.05 ms for horizontal, 244.93 ms for oblique and 225.27 ms for vertical target line segments. Whereas the two-factorial analysis of variance shows a significant effect of the factor orientation on FD_T ($F(2; 28) = 3.55; p = 0.042$), the Newman-Keuls test reveals that this effect can only be established for a comparison between horizontal and vertical ($R_{crit} = 13.941; p = 0.047$) and between oblique and vertical target orientations ($R_{crit} = 16.864; p = 0.050$), but not between horizontal and oblique orientations ($R_{crit} = 9.263; p = 0.799$). The interaction between target line segment length and orientation does not reach a significant level ($F(4; 56) = 1.14; p = 0.345$). Figure 10.10 (top left) visualises all means for FD_T for the three possible target orientations as a function of target length.

The statistical analysis of FD_C results in a highly significant effect of the factor target line segment length ($F(2; 28) = 27.62; p < 0.001$). The longer the target line segment is, the shorter fixation times are in proximity to the comparison stimulus: 494.41 ms for short, 373.55 ms for intermediate and only 321.95 ms for long targets are computed as FD_C means. No significant effect can be established for the factor target orientation ($F(2; 28) = 0.26; p = 0.771$). Accordingly, FD_C remains almost constant at 402.91 ms, 392.86 ms and 393.49 ms for horizontal, oblique and vertical orientations, respectively. All means are charted in Figure 10.10 (top right), separated for all possible combinations

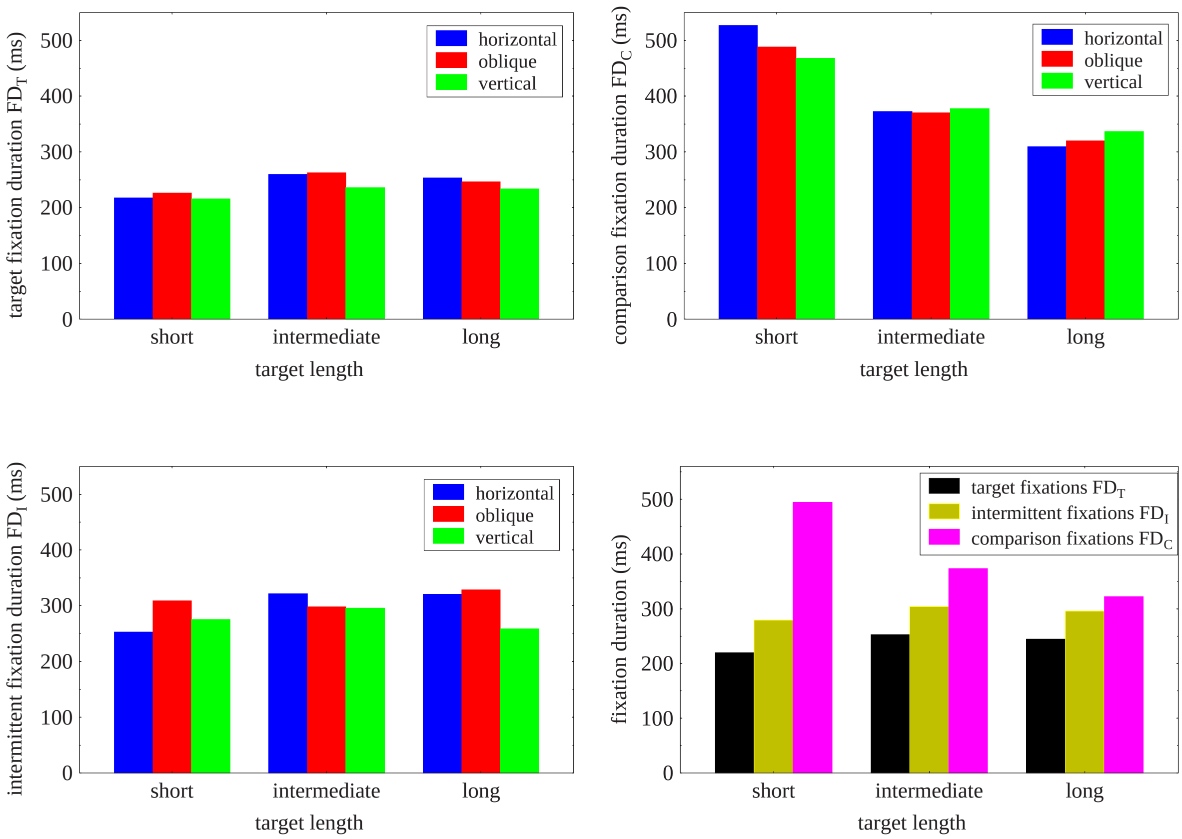


Figure 10.10: Local fixation durations in the target (FD_T, top left), the comparison (FD_C, top right) and the intermittent (FD_I, bottom left) sections as functions of target line segment length and orientation. Bottom right: Comparison of the local fixation duration in the target (FD_T), intermittent (FD_I) and comparison (FD_C) sections as a function of target line segment length.

of target line segment length and orientation. Again, the interaction between target line segment length and orientation does not reach significance ($F(4;56) = 1.26; p = 0.296$).

Finally, the statistical analysis of FD_I produces means of 279.11 ms for short, 304.12 ms for intermediate and 295.92 ms for long target line segments. When subjects fixate in between the two stimuli, the fixation duration is 291.07 ms for horizontal, 309.74 ms for oblique and 278.32 ms for vertical target line segments. As could be expected from these rather unsystematic distributions of FD_I, neither main effects of target length ($F(2;28) = 0.31; p = 0.738$) or orientation ($F(2;28) = 1.42; p = 0.256$), nor the interaction between these two factors ($F(4;56) = 1.46; p = 0.227$) reaches significance. Figure 10.10 (bottom left) charts the mean NF_I for the possible factor combinations.

Again, we will validate if significant differences exist between FD_T, FD_C and FD_I. The enhanced analysis of variance shows a significant effect for the factor "section" on the fixation duration ($F(2;28) = 21.17; p < 0.001$). On average, fixations last 239.06 ms in the target section, 291.81 ms in the intermittent section and 396.44 ms in the comparison section. The Newman-Keuls test reveals that significant differences indeed exist between all measures FD_T, FD_C and FD_I. In detail: FD_T vs. FD_I: ($R_{crit} = 51.739; p = 0.017$), FD_C vs. FD_I: ($R_{crit} = 56.130; p = 0.003$), FD_T vs. FD_C: ($R_{crit} = 48.749; p < 0.001$).

A particularly notable observation here is that fixations thus last significantly longer in proximity to the comparison than in proximity to the target line segment. The statistically significant differences are visualised in Figure 10.10 (bottom right) where FD_T, FD_C and FD_I are displayed in direct comparison for the three possible target lengths.

Number of Saccades between Hemifields SB

As far as the more “global” measures are concerned, let us finally consider the number of saccades between the two stimulus hemifields SB. With the number of fixations in the intermittent section being so low – there are many more “direct” saccades from one stimulus region to the other – it apparently makes more sense here to consider such “inter-stimulus” saccades (see also the following paragraph on “Number of Successive Fixations Within the Same Hemifield FW”) in order to obtain more reliable conclusions. The analysis of variance yields a significant main effect for the factor target line segment length on SB ($F(2; 28) = 44.85; p < 0.001$). When target line segments are short, 3.73 inter-hemifield saccades occur on average. For intermediate and long targets SB then increases to 4.92 and 5.74 saccades, respectively. The factor target line segment orientation does not exert a significant main effect on SB ($F(2; 28) = 2.69; p = 0.085$), only a slight tendency towards fewer saccades between the two stimulus hemifields emerges when targets are oriented obliquely or vertically (compared to horizontal target line segments): 4.99, 4.73 and 4.71 saccades are executed for the horizontal, oblique and vertical target orientations, respectively. No significant interaction between target line segments length and orientation can be observed ($F(4; 56) = 1.04; p = 0.396$). The detailed SB means for the combinations of target lengths and orientations are charted in Figure 10.11.

As we will discuss in detail in Section 10.3 later, these analyses of the number of fixations, fixation duration and the number of saccades between hemifields contribute to

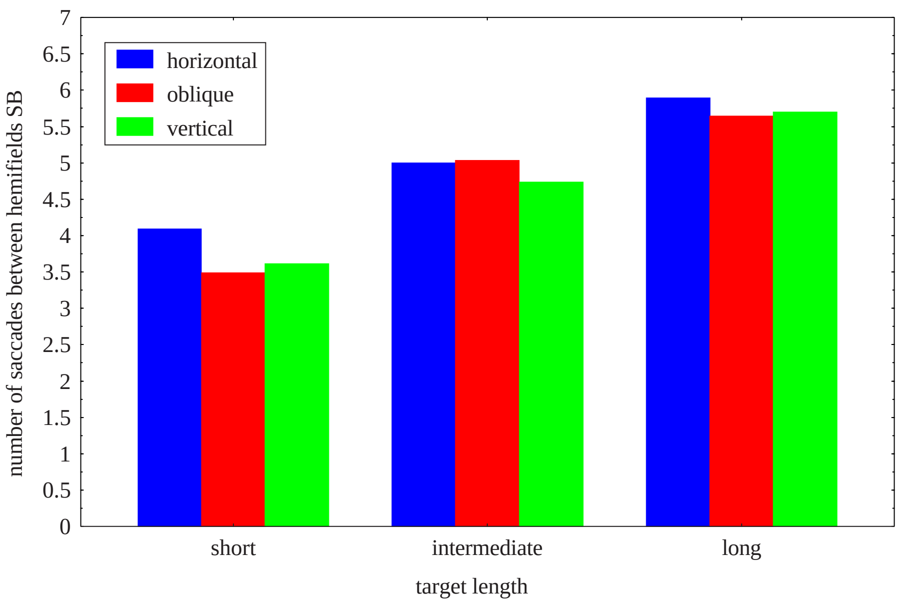


Figure 10.11: Number of saccades between stimulus hemifields SB as a function of target line segment length and orientation.

the understanding of the *global* processes that govern visual perception. The analyses of NF, FD and SB allow us to draw conclusions on the overall "visual effort" of foveal information processing required to solve a specific task. They provide insight into the general distribution of attention paid to the stimuli and how the manipulation of stimulus determinants could lead to systematic changes in these distributions. Even local numbers of fixations, such as NF_T, NF_C and NF_I and local fixation durations, such as FD_T, FD_C and FD_I rather contribute to the understanding of the more global aspects of visual perception – here, the comparison and matching of two line segments.

However, these clusters of "visual interest" then determine promising areas for a more detailed local investigation – beyond "simple" local NFs and FDs. The analysis of appropriate, more sophisticated *local* eye-movement parameters might thus clarify how within-cluster information is used to accomplish the given task. One of these advanced local measures is considered in the following section, namely the number of successive fixations within one hemifield FW. In conjunction with saccade length SL in particular we can hope to learn more about the perception of a single line segment and its memorisation for the subsequent matching with the comparison line segment in the other display hemifield – here, with particular respect to line segment length.

Number of Successive Fixations within the same Hemifield FW

As the name suggests, separate analyses will be computed for the target and the comparison stimuli hemifields rather than for the three previously defined sections. The absolute numbers of (all) fixations in the intermittent display section between the two line segments was below 1 already. Consequently, even lower values would be computed for FW_I. This does not constitute a sensible sequence of fixations for that region which can thus be excluded from the analysis. FW is therefore defined as the number of fixations that occur in succession within either the *target* or the *comparison hemifield* of the display before a shift to the other hemifield occurs. FW, averaging over both hemifields, will be analysed in order to test general effects of target length and orientation on this measure. Statistical analyses for FW_T and FW_C yield additional information with respect to possible differences between the visual analysis strategies for the target and comparison line segments.

The analysis of variance for FW yields a significant main effect for the factor target line segment length ($F(2; 28) = 12.76; p < 0.001$), but not for the factor target line segment orientation ($F(2; 28) = 2.48; p = 0.102$). Independent of the target orientation, on average 1.65 fixations occur in succession within each hemifield before the gaze moves to the other hemifield when short target line segments are presented. For intermediate length FW measures 1.81 fixations and for long targets 2.08 fixations. Independently of the target orientation, approximately 1.85 fixations occur within the same hemifield. Figure 10.12 visualises the means for the number of successive fixations within the same hemifield FW for the three target orientations as a function of target line segment length.

The separate analyses for FW_T and FW_C also result in a significant main effect for the factor target line segment length: ($F(2; 28) = 5.78; p = 0.007$) for FW_T and ($F(2; 28) =$

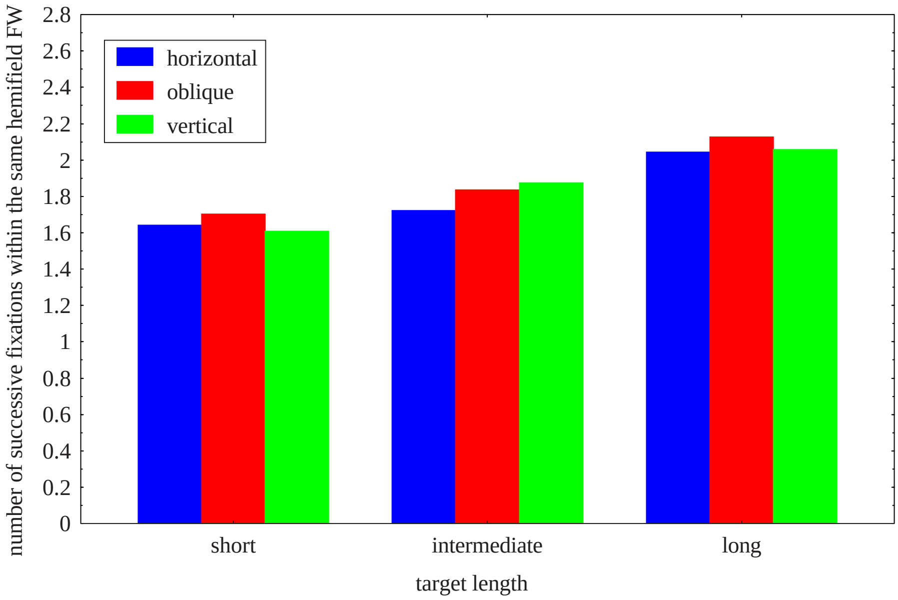


Figure 10.12: Average number of successive fixations within the same hemifield FW – either in the target or the comparison hemifield – as a function of target line segment length, separated for the three target orientations.

$16.51; p < 0.001$) for FW_C. FW_T is computed to 1.60, 1.50 and 1.67 for short, intermediate and long targets, respectively. In analogy, FW_C measures 1.72, 2.13 and 2.48 for the three target lengths. As some of the values for FW_T appear quite similar, it can be assumed that only a single contrast renders the differences between the three target length levels significant. Thus, the computation of a post-hoc comparison of means is certainly advisable. The Newman-Keuls test reveals that significant differences indeed exist only between intermediate and long targets ($R_{crit} = 0.091; p = 0.001$). Neither the comparison between short and intermediate ($R_{crit} = 0.112; p = 0.091$) nor that between short and long targets ($R_{crit} = 0.125; p = 0.186$) reaches significance.

The analysis of variance further shows a significant effect of the target orientation on FW_T ($F(2; 28) = 3.42; p = 0.047$). Again, the means of FW_T, 1.54 for horizontal target

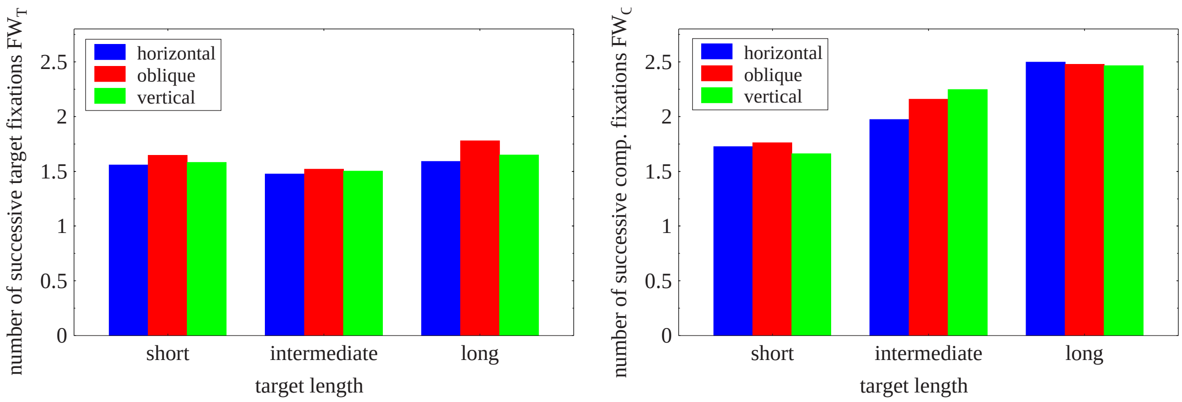


Figure 10.13: Number of successive fixations within the target hemifield FW_T (left) and within the comparison hemifield FW_C (right) as functions of target line segment length and orientation.

line segments, 1.64 for oblique and 1.58 for vertical ones, indicate that the significant effect can be attributed to only one contrast, namely that between horizontal and oblique targets. This is confirmed by the Newman-Keuls test ($R_{crit} = 0.079; p = 0.041$). With no significant effect of the target orientation on FW_C ($F(2; 28) = 0.96; p = 0.396$), approximately 2.11 fixations occur in the comparison hemifield independent of the target orientation.

For all three dependent variables FW, FW_T and FW_C the interaction between target line segment length and orientation does not reach significance. Figure 10.13 charts the means FW_T (left) and FW_C (right) for the possible factor combinations.

For the direct comparison of the numbers of successive fixations within the target and the comparison hemifields, the statistical analysis yields a significant main effect for the factor "hemifield" ($F(1; 14) = 17.71; p < 0.001$). Whereas only 1.59 successive fixations occur on average in the target hemifield (FW_T) before a shift to the other hemifield, FW_C measures 2.10 successive fixations.

The comparison further yields significant effects for the factor target line segment length ($F(2; 28) = 12.76; p < 0.001$) and for the interaction between hemifield and target line segment length ($F(2; 28) = 19.50; p < 0.001$). A post-hoc Newman-Keuls test to resolve the interaction effects in detail[2] reveals, however, that significant differences only exist in FW_C between the three target length levels and – as already visible in the significant main effect for the factor hemifield – between the individual values of FW_T and FW_C. In contast to FW_C, the differences in FW_T for the three target lengths are not classified as significant. This further allows us to conclude that the significant effect of

[2] Due to the large number of results for the factor combinations of the Newman-Keuls test in the form ($R_{crit} = ...; p = ...$), these individual values are not explicitly reported here.

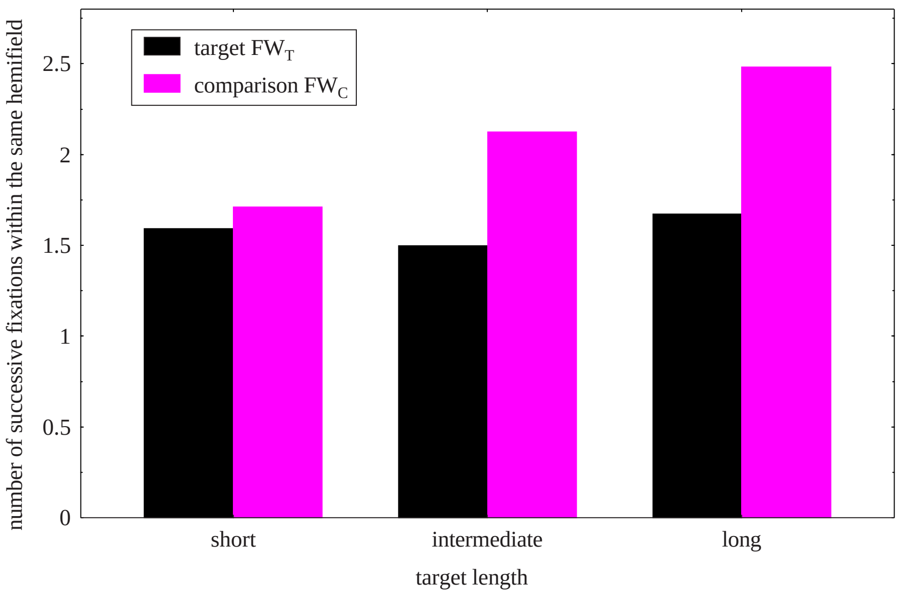


Figure 10.14: Comparison of the number of successive fixations within the target (FW_T) and the comparison hemifield (FW_C) as a function of target line segment length.

the factor target line segment length – when comparing FW_T and FW_C – can mainly be attributed to differences that exist between the absolute values for FW_T and FW_C and the differences FW_C shows for the three target lengths. FW_T varies far less with respect to these levels (cf. results for overall FW). To qualitatively support these dependences, Figure 10.14 illustrates the relevant means for the comparison of FW_T and FW_C as a function of target line segment length.

Saccade Length SL

As already indicated, the investigation of the saccade length SL should also help to understand the processes that govern the perception of a single line segment and its memorisation for the subsequent matching with the comparison line segment in the other display hemifield. Rather than considering a "global" SL, the "local" saccade lengths SL_T and SL_C are particularly promising. SL_T measures the average saccade length *within* the target hemifield, SL_C measures that *within* the comparison hemifield. As for FW, the saccade length in the intermittent section will not be considered – again, the insufficient number of fixations in that display section renders the computation of SL_I void. With respect to the more global understanding of the comparison process, the saccade length *between* the two relevant stimulus regions SL_b will be investigated first.

An analysis of variance tests the effects of the factors target line segment length and orientation on the saccade length between the two hemifields SL_b. It yields significant main effects for both factors on SL_b: ($F(2; 28) = 3.26; p < 0.001$) for target length and ($F(2; 28) = 3.47; p < 0.001$) for target orientation. The comparison of means shows that SL_b decreases from 21.21^o for short target line segments, through 20.82^o for intermediate to 19.54^o for long target line segments. A post-hoc comparison of means using the Newman-Keuls test produces significant differences between all levels of target length: ($R_{crit} = 0.354; p = 0.029$) for the comparison between short and intermediate lengths, ($R_{crit} = 0.446; p < 0.001$) for short vs. long lengths and ($R_{crit} = 0.421; p < 0.001$) for intermediate vs. long lengths. When the target line segment is oriented horizontally, SL_b covers 20.08^o, 20.43^o for oblique and 21.06^o for vertical targets. The differences between all target orientation levels are significant: ($R_{crit} = 0.199; p = 0.002$) for the comparison between horizontal and oblique orientations, ($R_{crit} = 0.240; p < 0.001$) for horizontal vs. vertical orientations and ($R_{crit} = 0.239; p < 0.001$) for oblique vs. vertical orientations.

In addition, the interaction between the two factors target line segment length and orientation also reaches significance ($F(4; 56) = 2.63; p < 0.001$). This can be attributed to the observation that, when short target line segments are presented, SL_b remains almost constant at approximately 21.2^o independent of the target orientation. A post-hoc comparison of means using the Newman-Keuls test confirms that no significant differences exist between the three orientation levels when the target is short: ($R_{crit} = 0.277; p = 0.430$) for horizontal vs. oblique orientation, ($R_{crit} = 0.234; p = 0.820$) for horizontal vs. vertical orientation and ($R_{crit} = 0.259; p = 0.565$) for oblique vs. vertical orientation. This not the case for intermediate and long targets. In case of intermediate length, SL_b increases slightly from 20.5^o for horizontal to 20.7^o for oblique and then significantly to 21.4^o for vertical target line segments. Such an increase in SL_b over the three orientations is even more pronounced – and significant between all levels – for long targets: From 18.5^o through 19.5^o to 20.6^o for horizontal, oblique and vertical target orientations, respectively. Accordingly, a Newman-Keuls test reveals significant differences between (almost) all orientation levels. Intermediate targets: ($R_{crit} = 0.355; p < 0.001$) for horizontal vs. vertical orientations and ($R_{crit} = 0.348; p < 0.001$) for oblique vs. vertical orientations. Long targets: ($R_{crit} = 0.349; p < 0.001$) for horizontal vs. oblique orientations, ($R_{crit} = 0.350; p < 0.001$) for horizontal vs. vertical orientations and ($R_{crit} = 0.353; p < 0.001$) for oblique vs. vertical orientations. Exception: No significant difference in SL_b can be found between horizontal and oblique orientations for intermediate target length ($R_{crit} = 0.279; p = 0.442$). Figure 10.15 charts the mean values of SL_b as a function of target line segment length, separated for the three target orientations.

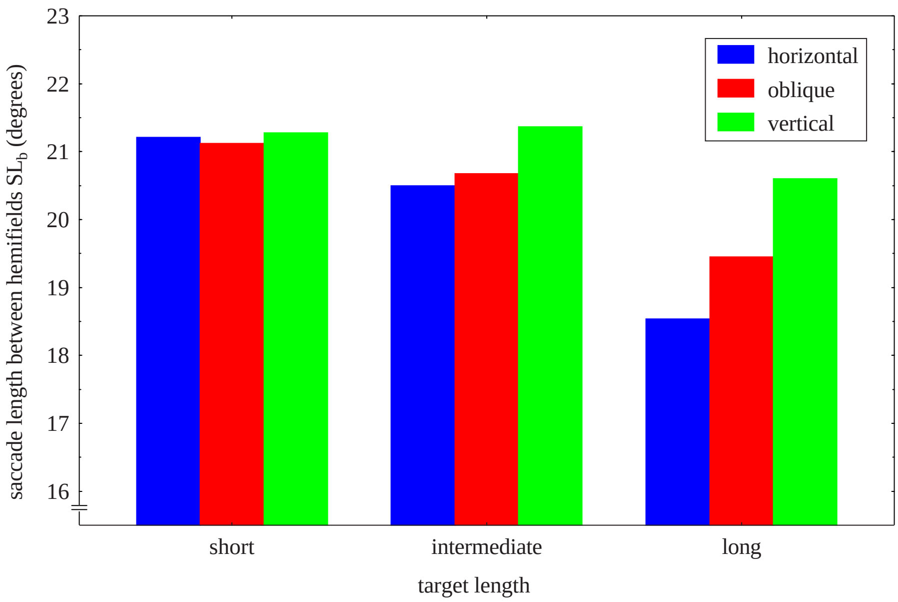


Figure 10.15: Saccade length between the two stimulus hemifields SL_b as a function of target line segment length and orientation.

Let us now consider the "local" saccade lengths. The analysis of variance for SL_T reveals a significant main effect for the factor target line segment length ($F(2; 28) = 1.45; p < 0.001$). Averaged over the three possible target orientations, the saccade length within the target section SL_T increases from 1.56^o for short target line segments through 2.31^o for intermediate to 2.94^o for long ones. A post-hoc comparison of means using the Newman-Keuls test produces significant differences between all levels of target length: ($R_{crit} = 0.446; p < 0.001$) for the comparison between short and intermediate lengths, ($R_{crit} = 0.427; p < 0.001$) for short vs. long lengths and ($R_{crit} = 0.357; p = 0.003$) for intermediate vs. long lengths.

Another main effect can be established for the factor target line segment orientation ($F(2; 28) = 1.54; p < 0.001$). Here, SL_T decreases from 2.94^o for horizontal to 2.02^o for oblique and further to 1.81^o for vertical targets. Here, only the differences between the following target orientation levels are significant: ($R_{crit} = 0.410; p < 0.001$) for the comparison between horizontal and oblique orientations and ($R_{crit} = 0.412; p < 0.001$) for horizontal vs. vertical orientations. Means of SL_T do not significantly differ for the comparison of oblique and vertical orientations ($R_{crit} = 0.338; p < 0.385$).

The interaction between target line segment length and orientation also exerts a significant effect on SL_T ($F(4; 56) = 1.62; p < 0.001$): Whereas SL_T remains almost constant at approximately 1.5^o for short targets, irrespective of their orientation, it significantly decreases from horizontal through oblique to vertical for intermediate – 2.97^o, 2.04^o and 1.87^o, respectively – and long targets – 4.32^o, 2.47^o and 2.04^o, respectively. Accordingly, a post-hoc comparison of means using the Newman-Keuls test confirms that no significant differences exist between the three orientation levels when the target is short: ($R_{crit} = 0.408; p = 0.671$) for horizontal vs. oblique orientation, ($R_{crit} = 0.315; p = 0.732$) for horizontal vs. vertical orientation and ($R_{crit} = 0.428; p = 0.613$) for oblique vs. vertical orientation. Furthermore, the Newman-Keuls test reveals significant differences between (almost) all orientation levels. Intermediate targets: ($R_{crit} = 0.487; p < 0.001$) for horizontal vs. oblique orientations and ($R_{crit} = 0.501; p < 0.001$) for horizontal vs. vertical orientations. Long targets: ($R_{crit} = 0.492; p < 0.001$) for horizontal vs. oblique orientations, ($R_{crit} = 0.499; p < 0.001$) for horizontal vs. vertical orientations and ($R_{crit} = 0.485; p = 0.007$) for oblique vs. vertical orientations. Exception: No significant difference in SL_T can be found between oblique and vertical orientations for intermediate target length ($R_{crit} = 0.305; p = 0.981$). Figure 10.16 (top left) illustrates the mean values for SL_T as a function of target length and orientation.

In contrast to SL_T, the analysis for the saccade length within the comparison stimulus hemifield SL_C shows a significant main effect for the factor target line segment length only ($F(2; 28) = 3.46; p < 0.001$). The comparison of means yields that SL_C increases from 1.40^o for short through 2.25^o for intermediate to 3.89^o for long target line segments. A Newman-Keuls test produces significant differences between all levels of target length: ($R_{crit} = 0.441; p = 0.001$) for the comparison between short and intermediate lengths, ($R_{crit} = 0.537; p < 0.001$) for short vs. long lengths and ($R_{crit} = 0.530; p = 0.003$) for intermediate vs. long lengths.

No significant effect on SL_C can be established for the factor target line segment orientation ($F(2; 28) = 0.006; p = 0.902$). Irrespective of the target orientation, SL_C measures approximately 2.6^o. (Remember that the comparison line segment is always oriented horizontally.) The interaction between target length and orientation does not reach a significant level either ($F(4; 56) = 0.05; p = 0.508$). Figure 10.16 (top right) illustrates the mean values for SL_C as a function of target length and orientation.

A comparison between SL_T and SL_C demonstrates no significant main effect for the factor hemifield ($F(2; 28) = 0.02; p = 0.519$). On average, saccade length measures 2.35^o within the target hemifield and 2.49^o within the comparison hemifield. However, as could be expected from the previous separate analyses of SL_T and SL_C, the interactions between the factors hemifield and target line segment length ($F(2; 28) = 1.36; p < 0.001$) and between the factors hemifield and target line segment orientation reach significance ($F(2; 28) = 0.54; p < 0.001$). Whereas SL_T and SL_C do not considerably differ for short

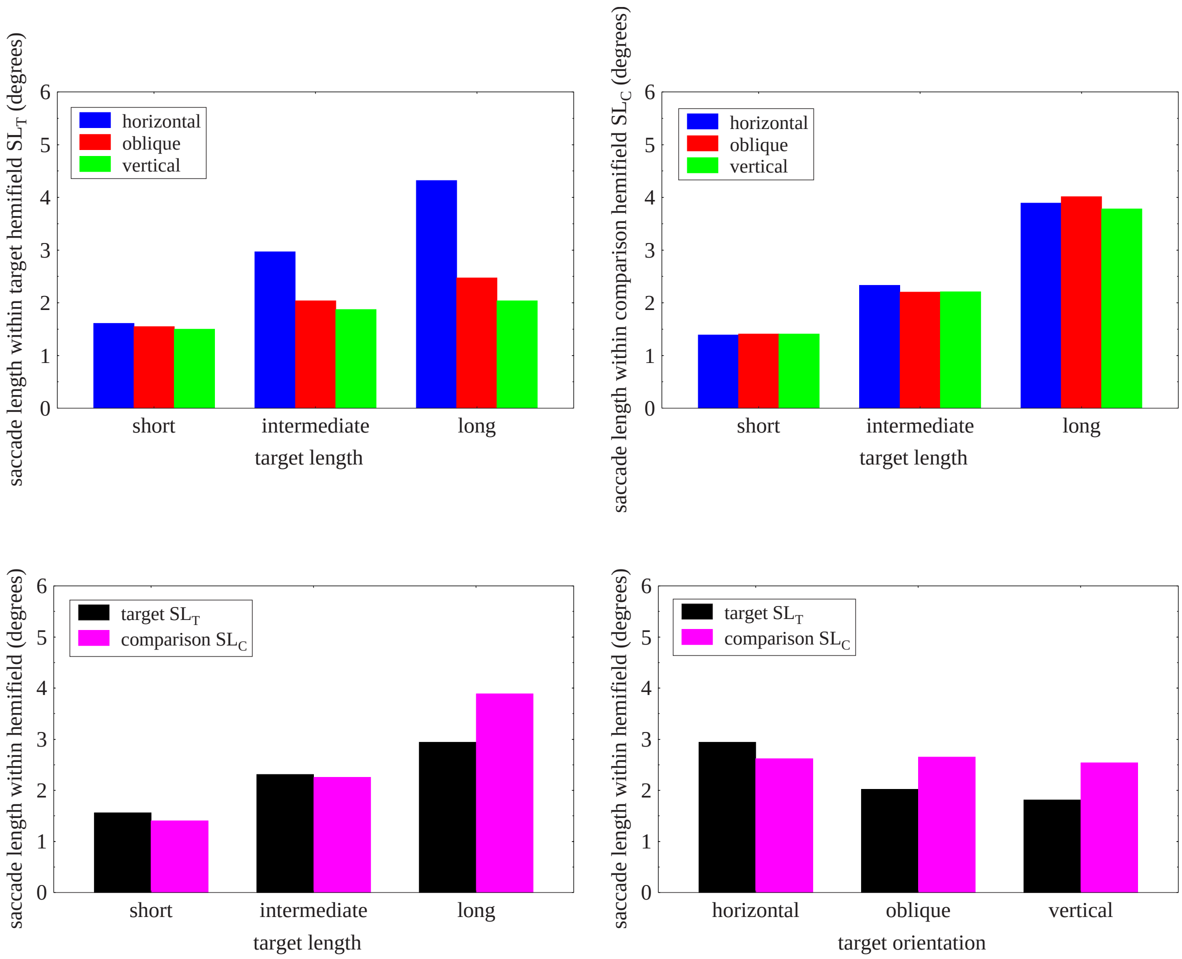


Figure 10.16: Saccade length within the target hemifield SL_T (top left) and within the comparison hemifield (top right) as functions of target line segment length and orientation. Comparison of the saccade length within the target (SL_T) and comparison (SL_C) sections as a function of target line segment length (left) and orientation (right).

and intermediate target lengths, SL_C is significantly longer than SL_T for long targets. With respect to the target orientation, SL_T decreases from horizontal through oblique to vertical targets whereas SL_C remains about constant, irrespective of the target orientation. A post-hoc Newman-Keuls test confirms these interaction details. However, the individual values are not explicitly reported here due to the large number of results for the factor combinations. Figure 10.16 illustrates the relevant means for the comparison of SL_T and SL_C as a function of target line segment length (bottom left) and orientation (bottom right).

10.3 Discussion and Conclusions

Let us recall the context within which the findings of the current Experiment S1 have to be considered and interpreted. One of the fundamental questions this study addresses concerns the *accuracy* that humans can achieve in the assessment and matching of line segment lengths in a simultaneous comparison scenario. With the variation of characteristic dimensions, namely length and – presumingly even more so – orientation, for this type of stimulus the study also aims to thoroughly investigate *visual illusory effects* on the assessment accuracy. The empirically acquired psychophysical data, such as the length deviation DL, allows us to manifest and exactly *quantify* the illusory effects induced by the various stimulus feature combinations. Rather than relying only on "classical" psychophysical results, the interpretation of additional *eye-movement* recordings should facilitate the understanding of the occurrence of these illusory effects and their extents. The results provide information on both the *"local"* intra-line-segment perception aspects as well as those concerning the *"global"* inter-line-segment comparison mechanisms of the length perception and assessment task. The discussion should provide insight in how far, for example, *"visual measurement"* of length, *"lean" fixation patterns* or *length extrapolation* strategies and *peripheral* processing influence length assessment and explain the observations. The discussion of eye-movement parameters may also help to understand certain *misjudgements* of line segment length, induced by the horizontal-vertical illusion. The interpretation of the sensorimotor data might further allow us to infer how *mental representations* of line segments and their relevant attributes are *generated, memorised, dynamically updated* and *recalled* for comparison. On aggregate, this should constitute a comprehensive image of the applied visual problem-solving strategy and thus make the fundamental steps of the *cognitive structure* for this type of visual comparison task more *transparent*. Finally, with a view to the subsequent Experiment S2, the data collected here provides the basis for determining which differences in line segment lengths should be easy or difficult to discriminate.

As before, we will briefly summarise the most outstanding effects that were observed in Experiment S1:

1. The lengths of the target line segments are *overestimated* throughout.
2. The factor target line segment length exerts a significant effect on all dependent variables, except for FD_I.
3. The factor target line segment orientation mainly exerts significant effects on specific dependent variables, namely on the local measures in the target hemifield such as FD_T, FW_T and SL_T. In addition, orientation effects on DL, ND_I and SL_b reach significance.

How can these observations and the associated, specific means for the factor combinations be interpreted, how do their relations and interactions form a comprehensive "image" of the processes involved in simultaneous dynamic length assessment and matching? To achieve this goal, we will now discuss and integrate the experimental results step by step in an attempt to gradually build up and complete such an image.

Compared to the reaction times measured in the eccentricity experiments E0, E1 and E2 (approximately 660 ms), RTs are now much longer (approximately 4620 ms). This is not very surprising and can mainly be attributed to the experimental task in Experiment S1 which is quite different from the previous ones. Not only the perception and memorisation of a single item and its length has to be accomplished, but also the comparison procedure. This procedure itself is a complex one, comprising memory recall and the actual feature comparison. The procedure also includes the dynamic length matching of the comparison stimulus. Furthermore, the number of inter-hemifield saccades SB indicates that the whole process is often re-iterated several times.

However, the higher complexity of the task might not account for the differences in RT alone. It must probably be considered as well that the free gaze condition favours other strategies to accomplish this task. With the gaze not being restricted, subjects in the current experiment can now follow more convenient, conceivably more *"natural"* visual strategies. The analyses of eye-movement parameters prove that such alternatives are indeed being used. Subjects *foveally* explore the relevant stimulus regions, generally yielding multi-fixation gaze trajectories – as will be discussed later. This detailed visual analysis must consequently lead to a further increase of RT.

The significant increase of RT from short through intermediate to long target line segments can be considered a first indicator for the *structure of the visual strategies* pursued during length assessment and adjustment. Even without knowledge of the supportive eye-movement data, it can thus be speculated that the increase of RT might be a consequence of an increase of the number of fixations that are necessary to assess longer line segments. If this assumption holds, we can further speculate that the visual strategy applied incorporates some sort of "visual measurement" of line segment lengths. It appears that this procedure requires an increasing number of fixations for longer line segments. Long line segments in particular can probably not be assessed as a whole; even two (end point) fixations might not suffice. Instead, a "step-by-step" measurement via intermittent fixations could be feasible, leading to prolonged response times. When such a strategy is indeed applied, the generation, memorisation, recall, comparison and matching or adaptation of the corresponding mental representation(s) becomes an increasingly complex cognitive task. The longer the respective line segments are, the more "constituents" have to be integrated into the representation. Such models might be more difficult to maintain or more prone to decay ("blur") and thus require additional (visual) verification, possibly manifested in an increasing number of inter-stimulus saccades – aspects then reflected in RT as well.

In contrast to the target length, the lack of a significant effect of the target orientation on RT does not allow for much speculation about possible visual strategies applied in dynamic line segment length assessment. However, the lacking orientation effect itself comes as a surprise when we take into account that the oblique and vertical targets induce a horizontal-vertical illusion – remember that the comparison is always horizontally oriented. These conditions could have been thought to constitute more challenging tasks than when comparing horizontal targets with horizontal comparisons. Subjects might just not be aware of the illusion; they obviously do not attempt to compensate for the difficult comparison conditions by spending more time on the task completion. Irrespective of the subjects' apparent unawareness of the visual illusion, differences in RT between the three orientation levels could also have been expected because switching between horizontal "scanning mode" in one hemifield and oblique/vertical mode in the other could have been assumed to be more challenging than for horizontal–horizontal comparisons where the scanning mode remains horizontal in both hemifields. Yet, none of these aspects is reflected in RT.

Indeed, the significant interaction effect between target length and orientation on RT – when targets are short RT decreases from horizontal to oblique and again to vertical targets, whereas RT remains almost constant for intermediate and long targets, irrespective of their orientation – seems to suggest the opposite. When the target line segments are short, subjects might actually try to accomplish the horizontal–horizontal matching task very accurately because this configuration appears to be easiest and thus most promising to "score" highly – although this extra accuracy does compromise RT, but not considerably. On the other hand, the combinations of oblique or vertical targets and horizontal comparisons might be assumed to be rather difficult so that achieving a high accuracy in matching the lengths would compromise RT too much and is not considered efficient. This, however, appears to apply only when short target line segments have to be assessed. For intermittent and long targets, the differences in RT between the different orientation levels fade, possibly – as discussed in the previous paragraph – as greater lengths could require a more thorough visual analysis anyway.

The *reluctance* of subjects to spend more time on the assumedly more difficult horizontal–oblique and horizontal–vertical comparisons than on the horizontal–horizontal ones could be one reason why the accuracy of the length matching, manifested in the relative length deviation DL, is better for the latter configuration of the target and comparison line segments. Furthermore, the increased length deviations when target and comparison line segments are not oriented co-linearly clearly indicate the presence of the horizontal-vertical illusion. The illusion yields its typical effects on perceived length, confirming a *significant length overestimation* of the target line segment when presented in oblique or vertical orientation. Subjects do obviously not succeed in ignoring or in compensating for the perceived length differences induced by the illusion – which they might not even be aware of. Thus, the incorrectly adjusted comparison lengths for obliquely and vertically oriented targets emerge as a logical consequence.

To understand the significant improvement of the assessment accuracy – i.e. the decrease of DL – for intermediate and, further, for long targets, compared to the length deviation for short ones, reference must be drawn to the discussion of RT. Viewed in conjunction with the prolonged reaction times for longer targets, the deceiving effects of the horizontal-vertical illusion might lessen. As the longer RTs are thought to indicate a more thorough visual analysis and subsequent mental representation of the stimuli, illusory effects could probably be easier realised and more conveniently compensated than during short inspection times. However, even then the illusion persists.

A finding that is certainly worth of discussion is that the *overestimation of target lengths also occurs for equally oriented segments.* One should have assumed that no "directional" effect, i.e. no over- or underestimation, should have occurred when both target and comparison are oriented horizontally. Let us consider possible explanations. As the two stimulus constituents do not differ with respect to their appearance (orientation, colour, thickness, intensity, etc.) on the display screen, it could be assumed that the adjustment procedure is responsible for the persisting overestimation. Starting point effects can be excluded as the initial lengths of the comparison stimuli were pseudo-randomly chosen so that they were shorter than the targets in fifty percent of the trials and longer in the remaining trials.

The decision to always present the target in the left hemifield and the comparison in the right hemifield probably yields a point for criticism. If this had been randomly varied, however, the initial localisation process – "Which line segment is the adjustable one?" – would certainly have caused more interference than the current procedure. Furthermore, no reference in literature could be found that indicates such side effects for these or similar experimental scenarios. This leaves the dynamic adjustment itself to cause the observed effect. It can only be speculated here that the "movements" of the comparison line segment when subjects dynamically adjust its length interfere with the preservation and recall of the memorised target line segment. The symmetric adaptation of the comparison – i.e. the line segment length changes symmetric to its center point and not at one end only – could worsen this interference. Visual attention is drawn to both end points of the comparison line segment which probably further complicates the matching with the target representation. Although the underlying principles remain unclear, this interference could distort the length representation in such a way that it is recalled longer than it was originally perceived and memorised – and thus also lead to the overestimation of horizontal targets. If this were true, it should hold for long lines in particular. Alternatively, and independent of the dynamic procedure, it could also be hypothesised that the *"decay"* of the representation between memorisation and recall generally leads to the expansion of the representation over (even short) time periods. To comprehensively explore these effects and validate the proposed hypotheses, it would be recommended to conduct a whole new series of experiments. It must be noted, however, that even when data is corrected for the base "offset", all above-mentioned effects persist and conclusions thus remain valid.

Let us now turn to the discussion of the *eye-movement parameters*. To what extent do they contribute to explaining the underlying processing mechanisms and perception principles which lead to the assessment–memorisation–adjustment/matching performance? How can eye-movement parameters account for phenomena such as the observed horizontal-vertical illusion? For most such parameters investigated here, both *global* and *local* measures are considered. This distinction is motivated by the assumption that corresponding – global and local – fundamental mechanisms characterise the assessment strategy. Globally, shifts of attention occur between the two stimulus constituents – the target and comparison line segments – which are then locally analysed. The associated global eye-movement parameters are assumed to yield information mainly on the task complexity and the general influence of the length and orientation factor levels on visual perception. The respective local measures should foster our understanding of the detailed visual perception of the stimuli themselves and how line segments are mentally represented.

The proposed distinction appears intuitive – both with respect to the assumed global and local strategies and with respect to the location of designated *"areas of interest"*. However, intuition cannot always be trusted, but requires some sort of validation. In the present case, the distribution of fixations (see Figure 10.6) indeed seems to lend support to the hypothesised strategy. Fixation points are cumulated in proximity to the target and comparison line segments. They also appear more numerous in an intermittent display section, extremely few fixations are located elsewhere. To demonstrate that this qualitative result holds, a cluster analysis (k-means clustering) was computed. With the help of this method it was thus possible to successfully validate the obvious "regions of interest" in a quantitative manner. These are otherwise often arbitrarily determined.

Furthermore, the clustering procedure and a subsequently applied principal component analysis (PCA) yield first insights into the *local* scanning strategies applied to assess the individual lengths of the stimuli. Due to the few fixations in the intermittent display section – compared to the numbers of fixations in proximity to the two line segments – the k-means clustering algorithm was only computed for two clusters. Thus, only two ellipses emerge as the result of the subsequent PCA (marked red in Figure 10.6). Their characteristic features, namely *shape* and, specifically, *location* and *orientation*, then indicate the following: The offset of the ellipsis' center of gravity suggests that *target line segments are only partially assessed foveally* and their *lengths extrapolated*, possibly taking into account *peripheral* visual information. The direction of the *offset towards the display center* for horizontal targets and towards the upper end point for oblique and vertical ones also speaks for an efficient visual strategy that takes into account *only that part of the target line segment that is closer to the comparison.*

The *shape* of the ellipsis makes clear that indeed *only parts of the target line segment* are considered, in particular when the targets are longer. In contrast, the axes along the first principal component of the "comparison ellipses" are actually longer than the corresponding comparison line segment. This can certainly be attributed to the changing lengths of the comparison during the dynamic length adaptation. For certain adaptation steps in the course of the adjustment procedure, the comparison length exceeded the final length.

Finally, the *orientations* of both the target and the comparison ellipses *resemble that of the respective line segments*. The target ellipses only reach such high co-linearity for horizontal targets whereas the comparison ellipses very accurately do so. However, even for oblique and vertical orientations, the target ellipses are correspondingly oriented. It can thus be assumed that *fixations indeed rather closely follow the line segments during the local scanning*, possibly even "visually measuring" the line segment lengths. However, as the distributions of fixations do not contain temporal information that determines the sequences of fixations, the assumption of "visual measurement" of line segment lengths – or parts thereof – must still be validated. The discussion of the numbers of successive fixations within the same hemifield FW should clarify this point. And indeed, as we will see soon, this measure supports the yet vague assumption.

The rather general discussion so far provided important information concerning the validity of the chosen measures. Based on the distributions of fixations and their parametrisations using computational methods such as clustering and principal component analysis, the results of the more specific eye-movement parameters can now be discussed "on safe ground". Furthermore, the previous discussion yielded first insights into both the globally and locally applied visual analytic strategies already. This encourages a further discussion that is guided by these premises.

In analogy to the presentation of the statistical results in the previous section, the overall number of fixations NF will be considered first. The significant increase of NF indicates that the task complexity rises the longer the target line segments – and, logically, the comparison ones also – become. However, as we noticed that the assessment accuracy improved for longer line segments, it is apparent that the greater visual effort "pays off". Subjects thus notice the more demanding task of assessing long line segments and successively compensate for it by a more detailed foveal visual analysis – gaze probably directed at the relevant stimuli rather than at blank space. If we assume that the awareness of the presence of a visual illusory effect also results in a more thorough analysis of the scene, a considerable increase in NF for oblique and vertical target would have been expected in an attempt to resolve the illusion. However, a dependence of NF on target orientation cannot be found. We must thus conclude that no attempt – in terms of extra visual/foveal effort – is made to compensate for the higher, illusion-induced complexity. The significant overestimation of the length of the target line segment when the horizontal-vertical illusion is present confirms that this is indeed the case.

The separate analyses of the local numbers of fixations in the target and comparison hemifields confirm these conclusions. Neither NF_T nor NF_C greatly varies with the target orientation as could have been expected following the argumentation for the overall NF. The increase of NF_T as well as NF_C for longer targets shows that not only one of the two variables is responsible for the increase of the overall NF from short through intermediate to long target line segments, but that both stimulus constituents require a more detailed visual analysis in order to achieve satisfactory length assessment and matching accuracy. The significant differences between the absolute values of NF_T and NF_C can only be attributed to the different requirements of the perceptual and cognitive tasks that subjects have to accomplish when looking either at the target or the comparison line segment. The visual assessment of the line segment in focus, the mental representation and storage of its length, the recall of the representation of the other line segment and its memorised length and the mental matching constitute the tasks in both hemifields. The *dynamic adjustment* of the comparison stimulus, however, requires *extra cognitive* and, as significantly higher values for NF_C demonstrate – compared to those for NF_T – *extra visual effort* as well. The process of length adaptation first requires a dynamic update of the comparison representation in accordance with the adaptation steps and, second, a repeated (mental) matching with the memorised target model and its length. Of these two additional processes, it is most likely that the first one can be characterised by further fixations. These will most certainly occur when the adapted comparison (length) has to be assessed again to yield the updated representation.

The very low absolute number of intermittent fixations NF_I renders the interpretation of this measure problematic, in particular with respect to the effects of the factors target length and orientation thereupon. On the other hand, it can reliably be claimed that the contribution of peripheral vision on global visual analytic strategies for this specific experimental setting is negligible. If intermittent fixations are assumed to be indicators for peripheral processing of the line segments in the target and comparison hemifields, simply too few occur to be possibly relevant for the assessment process. If these intermittent fixations are not considered relevant "anchor" locations for peripheral processing, but intermediate points "on the way" from target to comparison or vice versa, the significant effects of both target length and orientation on NF_I might indeed be interesting.

Two observations seem to speak in favour of the idea of intermediate fixations being "on the way" orientation points. First, the fixation duration FD_I is relatively short, probably too short to allow for explicit peripheral perception. This is also supported by the reaction times of the eccentricity Experiments E0–E2 which were considerably longer. Even more than FD_I, the angle between a saccade to and the subsequent one from an intermittent fixation point imply that such locations are only passed on the way: In 95% of all cases, this angle is larger than 135^o, indicating that no drastic direction changes occur between two successive saccades. This clearly speaks in favour of a sequence of *"in-line" fixations so that the "gaze passes through" the region between the two stimulus constituents "on the way"* from one line segment to the other. (When the angle between two successive saccades is considerably smaller then 90^o, the intermittent fixation rather marks a "turning point". The second saccade then leads back to where the first saccade started from.) It can now be assumed that even fewer intermittent fixations are necessary when long line segments are shown, in particular when they are horizontally oriented. They are then more closely located to each other than short ones and subjects do not need intermittent fixations to guide their gaze from one stimulus constituent to the other. That is exactly what the significant decrease of NF_I from short through intermediate to long target lengths and the significant increase of NF_I from horizontal through oblique to vertical target orientations demonstrate.

Let us also include the results of the PCA that describes the distribution of fixations in the target section. The analysis indicated that more fixations are located in proximity to the upper (inner) half of the target line segment if it is vertically (obliquely) oriented. When the gaze moves over from the horizontal comparison stimulus to an oblique or vertical target, or, more specifically, to its upper part, often an intermittent fixation might be required to change direction from the horizontal to an upwardly directed saccade. This process could also contribute to significantly higher numbers of fixations in the intermittent display section for oblique or vertical targets. However, no reference could be found in literature that reports a similar pattern of the inter-stimulus gaze trajectory.

Next, the discussion of the overall fixation duration FD and, specifically, its decrease from short through intermediate to long target line segments should yield further insight into the visual perception processes that govern the assessment of line segments and their lengths. In conjunction with the observation that fewer fixations occur when line segments are short(er), it can be concluded that *subjects obviously consider a visual scanning strategy that relies on fewer, but more "intense" fixations more efficient for the length assessment of line segments whose extent is restricted to a small local region.* The prolonged fixation times might also allow for some peripheral processing of those parts of the line segment that are not directly foveally perceived. In contrast, the data seems to suggest a spatially more detailed visual analysis for longer line segments that, in return, does not necessarily require such long fixation times as for short ones.

In addition, it could also be concluded that possibly more fixations occur in close proximity to each other when targets are longer. During these fixations, less visual information must be processed due to an overlap of the neighbouring, foveally scanned areas. Fixations could consequently be executed quicker. Furthermore, the only type of locally proximal fixations that would appear to make sense in the current setting are those that show a linear pattern. Fixations would probably be aligned along a line segment which might yield further support for an underlying strategy of "visually measuring" the line segments in order to obtain the relevant length information.

Alternatively, another explanatory approach should be considered. Assuming that short and long line segments require the same amount of processing, we could still expect more but shorter fixations for long lengths. This is because *larger objects induce larger shifts of attention, which, in turn, are more likely to cause saccades.* Consequently, more but shorter fixations should be expected.

The separation of FD into the local fixation durations shows that these conclusions must be further diversified and do not uniformly apply to both FD_T and FD_C. The considerable differences between these two measures, that fixations in the comparison hemifield last much longer than those in the target hemifield, can probably again be attributed to the influence of the dynamic adjustment procedure. A closer look at the procedure clarifies this. A joint analysis of the adjustment steps – also stored in the eye-tracker data file and synchronised with the eye-movement recordings – and the fixations shows that often only a *single* fixation occurs (never more than two) during each adjustment step (several of these are required to accomplish the whole assessment and matching task). The eye gaze thus remains stationary considerably longer than in the target hemifield where no such procedure "delays" fixation times.

Another interesting point for discussion with respect to FD_T and FD_C is that orientation effects on fixation times reach significance only when a fixation is "directly" influenced by orientation, i.e. for those fixations in the target hemifield. This significant influence on FD_T is not "carried over" to the comparison side, where line segments are always oriented horizontally. FD_C remains unaffected by targets that have oblique or vertical orientation. We may consider this as an indicator for independent assessment processes in the two hemifields. The visual analysis of the comparison does not take orientation effects into account which might possibly have been relevant for the compensation of the horizontal-vertical illusion – further support for the idea that such a compensation is not attempted which thus renders the observed illusory effect even more explicable.

What does the analysis of the number of saccades between hemifields SB tell about the "nature" of the simultaneous comparison process? As motivated earlier, not only the small number of fixations in the intermittent display section, but also the obtuse angle between saccades to and from these intermittent fixations allow us to define SB as a measure for saccades that *directly* link the two relevant stimulus constituents. SB is thus one of the essential parameters when it comes to understanding the global comparison process. SB is the "joint" between the individual local assessment processes of the stimuli themselves and describes the global *shifts of attention*. Their considerable increase for longer targets (but not for greater differences between target and comparison angles, i.e. when targets are oriented obliquely or vertically) makes clear that significantly more matching steps are required before subjects are satisfied with their estimate of the length of the comparison line segment. More specifically, the additional shifts of attention between the two stimulus constituents for longer target line segments indicate that extra local visual analysis of such line segments is required. Long line segments demand at least one extra local assessment operation. Again, subjects do not consider differently oriented target and comparison line segments to be worth any extra visual analysis, ignoring – or being unaware of – the illusion-induced higher complexity of the task.

In close relation to SB, the saccade length between the two stimulus hemifields SL_b also contributes to the comprehension of the global shifts of attention. The fact that the distance between the target and comparison line segments decreases the longer the line segments are is accordingly reflected by shorter inter-stimulus saccades. This is also true for the distance changes caused by orientation variation. In correspondence, SL_b increases when the target is oriented obliquely or vertically rather than horizontally. Although the extent of the changes in saccade lengths do not directly reflect the length differences between the levels of the target length – or the changes in distance between the two line segments when their orientations change – this observation can still be considered "evidence" that the gaze is indeed guided by the stimuli. This clearly speaks in favour of predominant foveal processing rather than a peripheral perception strategy on the global processing level. Furthermore, SL_b provides valuable hints towards which parts of the line segments might be primarily considered for the subsequent local visual analysis of the line segment. Specifically, it supports the discussion of the distribution of fixations and the corresponding principal component analysis: SL_b being generally shorter than the distance between the two line segments' center points (D_{TC}) suggests that probably the *innermost parts* of the line segment are evaluated, pointing to an efficient visual processing strategy. However, it is also known that long saccades – such as the inter-stimulus saccades in the present scenario – typically undershoot in all tasks. Some of the difference between SL_b and D_{TC} might thus have to be attributed to this observation.

So far, the discussion of results concerned variables which mainly contribute to the understanding of the more global aspects of line segment assessment, even when local measures derived from NF and FD were considered. However, the discussion also gave rise to various assumptions about the processes that could determine the *local* assessment of the individual length of the respective line segments, the generation and the recall of their internal representations. The following discussion of the local measures will shed more light on these principles so that finally a comprehensive image of global and local aspects involved in the simultaneous assessment and matching of lengths of line segments should emerge.

The joint discussion of the number of successive fixations within the same hemifield FW and the saccade lengths within that respective hemifield should now yield the desired insight into the local strategies pursued during the detailed visual analyses of the line segments. The overall FW strongly supports the previous assumption that about *two* fixations occur that could be required to *visually measure* the length of a line segment or at least parts thereof. As FW varies between approximately 1.7 for short targets and 2.1

for long ones, such a strategy appears to be particularly feasible for those line segments that cannot completely be assessed foveally, i.e. intermediate and long ones. However, even short line segments often require more than just one fixation in order to assess their length. The distribution of fixations implies that indeed locations on or at least in close proximity to the respective line segments are fixated – rather than just two arbitrary points within the target or comparison section. Similar observations are also common in other tasks as fixations almost never land in "empty space".

The separate analyses of FW_T and FW_C also demonstrate that in this dynamic adjustment scenario the comparison line segment in particular requires multi-fixation assessment. Compared to approximately 1.6 successive fixations in the target hemifield, 2.1 are executed in the comparison one. It appears likely that after each adjustment of the comparison line segment a new visual measurement of its length is performed. When long targets are presented, even more than just two successive fixations occur in proximity to the comparison (which is "long" as well). This could be interpreted as a local visual strategy in that hemifield that is constituted by an initial fixation point which is kept stable during the adjustment step – the prolonged fixation times FD_C speak in favour in this respect, too – and the subsequent new measuring of the current length of the comparison line segment.

In contrast, the average FW_T, which is well below two successive fixations, could indicate that typically the target is only once visually measured, assumedly by a two-fixation procedure at the beginning of each trial. Then, in the subsequent inter-hemifield comparison steps, the initially generated and memorised mental representation of the target might only require a *"refreshing"*. Not always, but in most cases, this can probably be realised by executing just a single fixation in proximity to the target. The target representation thus refreshed is then used for the following mental comparison with the accordingly updated mental representation of the comparison line segment. The effects of target length and orientation on FW_T demonstrate, however, that for obviously "difficult" comparisons, i.e. when the line segments are either long or not co-linearly oriented, the target line segment also requires a more thorough local visual assessment and representation "refreshing". On the other hand, short line segments that can be perceived foveally do allow for a simplified local assessment strategy in the comparison hemifield and, even when the target is obliquely or vertically oriented, in the target hemifield as well.

Finally, the discussion of saccade lengths within each hemifield should resolve remaining doubts about the local visual strategy that is assumedly applied. The discussion should further yield insight into which parts or which ratio of the line segments are taken into account for length assessment. It might also answer the question if, for example, "lean" visual scanning strategies and extrapolation mechanisms, maybe incorporating peripheral visual information processing, are applied. In this respect, it is promising to find that *saccades within the target hemifield have indeed about the same length as the target when it is short* (1^o). This clearly speaks in favour of the suggested *visual measurement mechanism* of line segments' lengths. As closer investigation further reveals that these short target measuring saccades are actually longer – 1.6^o for horizontal targets, 1.55^o for oblique ones and 1.5^o for vertical ones on average – than the respective physical target lengths. This would then link the *horizontal-vertical illusion* effects to *oculomotor* processes which may account for the overestimation even of horizontal targets.

Why exactly is that so? Let us consider that the (physical) length of a short horizontal target line segment (1^o) is internally represented and memorised as the length of the corresponding "measuring saccades" in the target hemifield, i.e. as 1.6^o (see above). This representation is being recalled during the assessment of the comparison and its adaptation performed accordingly. The comparison length is thus adjusted longer than the physical target length and consequently yields the overestimation effect for horizontal targets.

The same phenomenon conceivably affects the horizontal-vertical illusion as well: In accordance with the saccades "measuring" oblique and vertical target lengths, the adaptation of the comparison is accomplished. For short targets, the accordingly generated mental representations of the target length is again longer than their physical length. Again, these representations are recalled to adjust the comparisons and thus contribute to the observed overestimation effect.

It can be assumed that these principles do not uniquely apply to the short targets that we have discussed so far. However, when targets have intermediate or long length, the situation appears to be somewhat more complicated. Only *fractions* of the line segments are *visually measured*, these fractions being significantly smaller, i.e. shorter, than the entire length of the target line segment. Although these saccade lengths within the target and the comparison hemifields significantly vary, their absolute values are not completely different. We can therefore assume that the length assessment and matching process is constituted by comparing the memorised representation of the target fraction with a designated comparison fraction. This seems more likely than the also possible comparison of a *fraction* of one line segment with the *whole* length of the other. Such a process would then require the additional, *explicit* (mental) representation of a *"multiplication" factor* to relate the ratio of the represented fraction to the overall length of the line segment.

Instead, the proposed strategy of a "fractional comparison" (for both line segments) does not necessarily require an explicit, but rather an *implicit ratio representation*. That is because it must still be ensured that an equally sized fraction of the comparison line segment is considered for the comparison with the recalled representation of the memorised fraction of the target length. This would then require determining and at least implicitly representing the size of the fraction. As, in particular for oblique and vertical targets, very little foveal scanning of the outermost half of the line segment is observed, it must be assumed that the essential information for storing such fraction data is acquired peripherally. The fraction data to be stored might thus be represented in terms of the distance between the peripherally perceived outermost end point and one of the fixations that contribute to the actual "measuring saccade" of the respective line segment. This clearly indicates that the *decomposition* of line segments also presents a fundamental assessment mechanism in simultaneous, free gaze comparison scenarios that allow for the foveal assessment of line segment length. The decomposition might further guide *saccade planning*, in particular for measuring saccades: While fixating one end point of a line segment, the other end point is likely to be peripherally assessed and serve as a "landmark" location for the landing point of a measuring saccade. The actual landing point will usually not be the landmark (end) point. In accordance with the fractional visual measurement strategy the saccade will rather aim at an *intermittent* location – at least for longer line segments.

Furthermore, it must be assumed that although such an efficient visual strategy of length assessment is pursued for all orientations when targets have intermediate or long lengths, larger fractions are taken into account for the assessment of horizontal targets. This appears to facilitate the comparison and allows for the more accurate assessment of horizontal target lengths. The relatively small differences between saccade lengths within either the target or the comparison hemifield confirm this. They also present more evidence for the fact that the – here fractional – visual measurement is pursued in both hemifields to achieve the length matching. In fact, the differences between SL_T and SL_C can be considered valid accuracy measures and represent an equivalent measure – at least qualitatively – to the length deviation DL.

In comparison to SL_T for horizontal intermediate and long targets, very much smaller line segments fractions are taken into account when the targets are either obliquely or vertically oriented. According to the perception strategy described above, this consequently means more peripheral information processing which must also be achieved in even further peripheral regions. With respect to the findings of the eccentricity Experiments E0–E2, it is thus not unexpected that this obviously renders the length assessment in the current scenario less accurate – clearly visible in SL_C. As SL_C is considerably larger than SL_T, this again confirms that possible causes for the horizontal-vertical illusion might already be found in *oculomotor* processes.

10.3.1 Summary

The discussion has demonstrated that the perception principles that determine the simultaneous comparison of line segment length, paired with a dynamic length matching procedure prove a lot more complicated than could initially have been expected. The empirical findings yield that even "simple" line segment stimuli and the assessment of their basic features such as length trigger diverse, characteristic visual analysis patterns guided by elaborate strategies, in general also strongly influenced by "secondary" stimulus determinants.

All data support local, *foveal "visual measurement"* as a fundamental principle to assess line segment length within the present scenario. This visual measurement principle is generally characterised by *two successive fixations* within the same hemifield. More specifically, these fixations are located in close proximity to or rather "on" either the target or the comparison stimulus. The saccade length between the two fixations closely *coincides* with the overall length of the respective line segment when it is short or, when longer, often only covers the *innermost fraction* of the line segment. In the latter case only, additional information on the *size* of the fraction in relation to the overall length must be stored along with the mental representation of the saccade length for the subsequent comparison. As discussed, this could probably have been achieved by incorporating *peripherally* perceived information on the outermost end point of the line segment in question and requires the *decomposition* of the line segment. The "lean" visual exploration strategy is probably pursued for reasons of efficiency. Rather than exhibiting "laziness" by executing only short and/or infrequent saccades, it can instead be assumed that the proposed strategy is followed because it might yield "better" matching results than step-by-step foveally measuring the whole line segment and storing a multiple-fixation/saccade representation. This would certainly demand greater memory "effort" in order to store the data and, in particular, to maintain and update the various representations.

Eye movements indicate that after the visual measurement of one of the two stimulus constituents and the generation of a corresponding mental representation, attention *directly shifts* to the other line segment. The comparison stimulus is analogously assessed, i.e. visually measured, and the correspondingly generated representation *mentally compared* with the previously memorised one. If the two representations are not found to match in length, the comparison is adjusted and the mental comparison is *executed again* with the *updated* comparison representation. This procedure can be re-iterated several times until the two representations of the target and comparison line segments are found to match in length. Fixation data also suggests that sometimes intermittent saccades to the target line segment occur (single fixations only), probably to *"refresh"* the initially memorised target representation – in particular when numerous adjustment steps are necessary to match the comparison length.

The discussion also yields some conclusions that must possibly be attributed to the dynamic adjustment procedure. This renders the procedure at least critical when assigning specific observations – as intended – solely to the actual line segment assessment task. Results suggest that, for example, the extended fixation times FD and the distributions of fixations that determine the shape of the ellipses the PCA yielded in the comparison hemifield are influenced by the dynamic procedure. The overestimation of horizontal targets can possibly be attributed to the dynamic procedure as well – although the visual measurement strategy was later found to more plausibly account for it. On the other hand, the dynamic adjustment procedure proves indispensable in determining the accuracy of line segment length perception. Not only does it yield the required data to determine easy and difficult discrimination conditions in the final Experiment S2, but the stimulus-induced horizontal-vertical illusion could also be quantified. More interestingly with respect to the illusory effects, the analysis of eye-movement data even hints at new aspects to be considered in explanatory approaches: Taking the visual measurement strategy into account, in particular saccade lengths indicate that mental representations that are longer than the physical lengths of the line segments are stored and referred to for comparison and matching. This may then yield the typical overestimation of oblique and vertical line segments induced by the illusion.

In summary, the current scenario not only allows for the elucidation of typical visual scanning strategies and the influence of feature variations thereupon in order to understand the perception principles of line segment length assessment. It also produces insight into the extent of the stimuli-induced horizontal-vertical illusion effects and provides new approaches to assist its understanding. With data regarding the accuracy of the length matching process now available, this should allow us to determine length perception principles in even greater detail in Experiment S2. Its static scenario should eliminate the "side-" effects induced by the current dynamic adjustment procedure. It apparently distracts subjects from the "pure" length perception task and makes it often difficult to assign specific observations solely to the dynamic adjustment process or to the actual line segment assessment task.

Chapter 11

Experiment S2: Simultaneous Binary Length Comparison

The second experiment of this series exploring simultaneous length assessment focusses on the effects of length similarity on visual line segment perception and processing. Depending on the level of similarity of two simultaneously presented line segments, it can be assumed that rather different processing strategies are pursued to decide, for example, which of the two is the longer. Specifically, we hypothesised two distinct strategies, namely a *holistic* and an *analytic* one.

Comparing two line segments that clearly *differ* in length, i.e. show a *low* length similarity, obviously constitutes an *easy* discrimination task. Instead of talking of a low similarity level, the notion of a high discrimination level can also be used. It appears to be intuitively clear that solving this simple task requires mostly *holistic* perception processes. As discussed in detail in Chapter 9, these are probably characterised by an efficient, "lean" visual exploration strategy, manifested in *sparse* eye movements and much *peripheral* processing.

When the two line segments do *not* significantly vary in length, i.e. show a *high* similarity level (equivalent to a low discrimination level), the discrimination task is *difficult* and demands a thorough visual *analysis* of the scene. This analytic strategy, if indeed pursued, will be characterised by a type of visual exploration that is manifested in eye movements very different to those for holistic processing: As already explained in more detail in Chapter 9, numerous (overt) shifts of attention can be expected in order to *foveally scan* the two line segments and their supposedly relevant features, helping to solve the length discrimination task.

These two opposing solution strategies (cognitive level) should lead to different visual processing strategies (perceptive level) and manifest in distinct differences in eye-movement parameters (sensorimotor level) and gaze trajectories. To validate these assumptions, we explore the paradigm of simultaneous comparison paired with the psychophysical method of constant stimuli in Experiment S2. This experimental paradigm creates more valid conditions for an eye-movement investigation than the method of adjustment used in Experiment S1. The elimination of the dynamic process of line segment length adjustment should facilitate the monitoring and understanding of comparison processes and the influence of line segments attributes thereupon. This *static* procedure should in particular be beneficial for the interpretation of eye movement-patterns and associated attention processes.

Results from the previous experiment make a valuable contribution to establishing the easy and difficult conditions. The adjustment accuracies of the line segment lengths in Experiment S1 can be used to infer which differences between line segment lengths are difficult to distinguish – obviously those that lie within this accuracy – and which are easy to distinguish – those that lie considerably outside the accuracy – the discrimination/similarity conditions can be determined accordingly. More specifically, the key determinants will be the mean values for the length assessments and their respective standard deviations measured in Experiment S1. Difficult discrimination conditions will thus be those where the difference between the target and the perceived comparison line segment lengths does not exceed the *standard deviation boundaries* of the length adjustment. In the easy discrimination condition, this difference will be a *multiple* of the standard deviation in order to yield clearly varying lengths for the target and comparison line segments, respectively.

For statistical analysis, the relevant eye-movement data, such as number of fixations NF, fixation duration FD or saccade length SL (for details see Section 3.4.2) will be statistically analysed, gaze trajectories will be qualitatively analysed. However, reaction time should also be suitable for yielding reliable information regarding the two processing strategies. Before these analyses can be computed, however, it must be ensured that the chosen discrimination parameters yield valid conditions, i.e. that supposedly easy tasks are indeed easy and difficult tasks are indeed difficult. Therefore, the discrimination parameters will be empirically determined and evaluated prior to the actual Experiment S2 by analysing the correctness of the subjects' responses in a pre-experiment.

11.1 Determination of Discrimination Parameters

From Experiment S1, we obtained the perceived lengths of line segments for all possible combinations of lengths and orientations, i.e. the lengths of the comparison line segments LC_{S1} that subjects adjusted so that they matched – in their belief – those of the simultaneously presented target line segments LT_{S1}, i.e. $LC_{S1} = LT_{S1}$. As results from Experiment S1 demonstrated, however, the adjustments did not coincide with the original target length. Instead, they were characterised by significantly different means, i.e. $LC_{S1} \neq LT_{S1}$, and corresponding standard deviations $\sigma_{LC_{S1}}$. We can thus assume that the simultaneous presentation of the previously shown target line segments with lengths $LT_{S2} = LT_{S1}$ and the corresponding comparison line segment with lengths of

$$LC_{S2} = LC_{S1} \pm \sigma_{LC_{S1}} \tag{11.1}$$

is a rather difficult task, as the two line segments obviously appear quite similar in length. This defines the high similarity condition[1].

An obvious definition for the low similarity condition, i.e. one that renders it easy for subjects to decide which of the two line segments is the longer, would be to define the lengths of the comparison line segments shown in Experiment S1 as

$$LC_{S2} = LC_{S1} \pm \lambda \cdot \sigma_{LC_{S1}} \tag{11.2}$$

with λ a suitable factor greater than one. However, it must be ensured that λ is defined so that the lengths of the comparison line segments are "sufficiently" different from those of the target line segments in order to constitute "reliable" easy comparison conditions. This can be achieved by analysing the correctness of the discrimination task for different factors. If the percentage of correct answers lies above a certain threshold, let us say 95%, we will assume that we established the appropriate factor and that the task is indeed an easy one. As we did not intend to create conditions that are too easy, the minimum factor λ to achieve 95% correctness of subjects' responses was determined in a pre-experiment. As the stimuli and procedure employed in this pre-experiment were almost identical to those of the following Experiment S2, we will only briefly describe the experimental setting at this point (for details see Section 11.2).

Subjects viewed two simultaneously presented line segments. A target line segment in various lengths and orientations was shown in the left hemifield of the display, a comparison line segment in the right hemifield, always in horizontal orientation. The length of the comparison line segment was computed according to Equation 11.2. The equation's constituents LC_{S1} and $\sigma_{LC_{S1}}$ were determined in Experiment S1 and are functions of the independent variables target length and orientation. Furthermore, λ was systematically varied as an additional independent variable. The factor levels for λ were set to either 2, 3, 4, 5 or 6. With each of these $3 \times 3 \times 5 = 45$ possible combinations of the three independent variables shown twice, each subject had to assess 90 stimuli pictures and decide which of the two line segments was longer.

The subsequent analysis, where only the overall correctness of the discrimination (DC, in percent) was investigated, yielded the following results:

λ	DC (%)
2	81
3	89
4	96
5	100
6	100

According to the suggestion to choose λ so that at least 95% of the subjects' responses are correct, it appears to be reasonable to set $\lambda = 4$. In order to add more variation to

[1]With $LC_{S1} \neq LT_{S1}$ and $\sigma_{LC_{S1}} \neq 0$, Equation 11.1 allows for the computation and display of comparison line segments in Experiment S2 that have the same *physical* lengths as the simultaneously shown target line segments with lengths $LT_{S2} = LT_{S1}$. However, according to the findings of Experiment S1, subjects should not *perceive* them as equally long.

the lengths of the comparison line segments, LC_{S2} will be determined as

$$LC_{S2_{easy}} = LC_{S1} \pm \lambda_{easy} \cdot \sigma_{LC_{S1}} \qquad with \;\; \lambda_{easy} \in [4,5] \tag{11.3}$$

$$LC_{S2_{diff}} = LC_{S1} \pm \lambda_{diff} \cdot \sigma_{LC_{S1}} \qquad with \;\; \lambda_{diff} \in]0,1] \tag{11.4}$$

for the easy and difficult conditions, respectively. Thus, all preliminaries for the investigation of similarity effects on the perception of simultaneously presented line segment length are established. The following sections now discuss the respective Experiment S2.

11.2 Method

11.2.1 Subjects

The subjects were thirty-four experimentally naive students – eighteen male and sixteen female – from the University of Bielefeld. Their average age was 26.9 years. All subjects had normal or corrected-to-normal vision and no pupil anomalies. The subjects were paid for their participation in the experiment.

11.2.2 Stimuli

Stimuli were presented on a computer screen with the same physical size and spatial resolution as in Experiment S1. Furthermore, most other stimuli specifications with regard to their colour, line segment thickness, length and orientation of the target line segments and presentation location remained unchanged. Again, the target line segment was always presented at the center of the left hemifield of the display and the comparison in a horizontal orientation at the center of the right hemifield. In Experiment S2, however, the length of the comparison line segment could not be changed, but was set to a fixed measure. This length was chosen in relation to that of the target line segment so that it yielded either a difficult or an easy discrimination task (see previous section). Specifically, the comparison line segment lengths LC for the possible combinations of target line segment lengths LT (columns) and orientations ORI (rows) were set to a random value within the intervals as charted in Table 11.1, separated for the easy (LC_{easy}, top) and difficult (LC_{diff}, bottom) conditions. In accordance with the Equations 11.3 and 11.4, the upper row for each factor combination was computed as

$$LC_{easy/diff} = LC_{S1} - \lambda_{easy/diff} \cdot \sigma_{LC_{S1}} \tag{11.5}$$

and the lower row as

$$LC_{easy/diff} = LC_{S1} + \lambda_{easy/diff} \cdot \sigma_{LC_{S1}} \tag{11.6}$$

with LC_{S1} and $\sigma_{LC_{S1}}$ computed in Experiment S1 and $\lambda_{easy/diff}$ determined in the previous section. Figure 11.1 shows typical stimulus pictures for the easy (top) and difficult (bottom) discrimination conditions.

ORI	LC_{easy}		
	short ($LT = 1^o$)	intermediate ($LT = 6^o$)	long ($LT = 11^o$)
	$(LC_{S1} = 1.08^o)$	$(LC_{S1} = 6.26^o)$	$(LC_{S1} = 11.22^o)$
0^o	$[0.43^o \; , \; 0.56^o[$	$[3.71^o \; , \; 4.22^o[$	$[8.07^o \; , \; 8.70^o[$
	$]1.60^o \; , \; 1.73^o]$	$]8.30^o \; , \; 8.81^o]$	$]13.74^o \; , \; 14.37^o]$
	$(LC_{S1} = 1.13^o)$	$(LC_{S1} = 6.90^o)$	$(LC_{S1} = 12.09^o)$
45^o	$[0.48^o \; , \; 0.61^o[$	$[3.85^o \; , \; 4.46^o[$	$[7.59^o \; , \; 8.49^o[$
	$]1.65^o \; , \; 1.78^o]$	$]9.34^o \; , \; 9.95^o]$	$]15.69^o \; , \; 16.59^o]$
	$(LC_{S1} = 1.20^o)$	$(LC_{S1} = 6.70^o)$	$(LC_{S1} = 11.95^o)$
90^o	$[0.60^o \; , \; 0.72^o[$	$[3.50^o \; , \; 4.14^o[$	$[7.10^o \; , \; 8.07^o[$
	$]1.68^o \; , \; 1.80^o]$	$]9.26^o \; , \; 9.90^o]$	$]15.83^o \; , \; 16.80^o]$

ORI	LC_{diff}		
	short ($LT = 1^o$)	intermediate ($LT = 6^o$)	long ($LT = 11^o$)
	$(LC_{S1} = 1.08^o)$	$(LC_{S1} = 6.26^o)$	$(LC_{S1} = 11.22^o)$
0^o	$[0.95^o \; , \; 1.08^o[$	$[5.75^o \; , \; 6.26^o[$	$[10.59^o \; , \; 11.22^o[$
	$]1.08^o \; , \; 1.21^o]$	$]6.26^o \; , \; 6.77^o]$	$]11.22^o \; , \; 11.85^o]$
	$(LC_{S1} = 1.13^o)$	$(LC_{S1} = 6.90^o)$	$(LC_{S1} = 12.09^o)$
45^o	$[1.00^o \; , \; 1.13^o[$	$[6.29^o \; , \; 6.90^o[$	$[11.19^o \; , \; 12.09^o[$
	$]1.13^o \; , \; 1.26^o]$	$]6.90^o \; , \; 7.51^o]$	$]12.09^o \; , \; 12.99^o]$
	$(LC_{S1} = 1.20^o)$	$(LC_{S1} = 6.70^o)$	$(LC_{S1} = 11.95^o)$
90^o	$[1.08^o \; , \; 1.20^o[$	$[6.06^o \; , \; 6.70^o[$	$[10.98^o \; , \; 11.95^o[$
	$]1.20^o \; , \; 1.32^o]$	$]6.70^o \; , \; 7.34^o]$	$]11.95^o \; , \; 12.92^o]$

Table 11.1: Lengths of the comparison line segments LC for all combinations of target line segment lengths and orientations as shown in Experiment S2. The top table shows LC for the easy discrimination task, the bottom table for the difficult discrimination task (σ values obtained in Experiment S1).

11.2.3 Apparatus

The apparatus used was the same as in Experiment E0.

11.2.4 Procedure

The procedure in Experiment S2 closely resembled that in Experiment S1, both with respect to the employment of the eye-tracker device and the stimulus presentation in general. However, the psychophysical method of constant stimuli employed here required changing the procedure in some respect.

After the initial phase of eye-tracker setup and calibration, the actual experiment

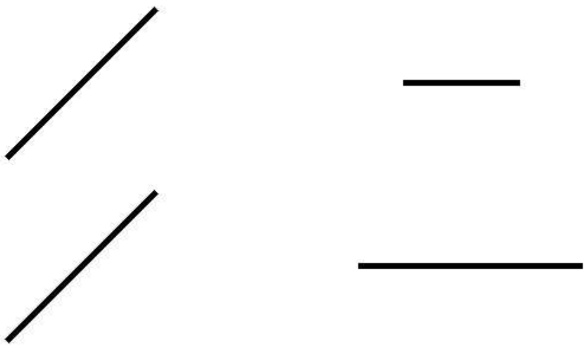


Figure 11.1: Typical stimulus pictures in Experiment S2. Subjects had to decide which of the two line segments was longer. The similarity of the two line segments was either low (top) or high (bottom), inducing either holistic or analytic processing strategies, respectively.

commenced. As before, each trial started with the presentation of a fixation point at the center of the screen (Frame 1, see Figure 11.2). 700 ms after fixation point onset, the two line segments were displayed simultaneously in the left and right hemifields (Frame 2). The fixation point disappeared 200 ms thereafter. The subjects were instructed to make a simple binary decision as to which of the two line segments they perceived as being longer. Subjects then pressed the respective mouse button to communicate their decision – left button for longer target (left hemifield of the display) or right button for longer comparison (right hemifield)– and to start the next trial.

The target line segment was always shown in the left hemifield, the comparison line segment – in horizontal orientation – in the right hemifield. The orientation and length of the target line segment and the length of the comparison line segment, i.e. the similarity level, were varied according to the respective independent variables. No gaze restrictions applied, subjects could move their gaze freely across the whole screen. Figure 11.2 illus-

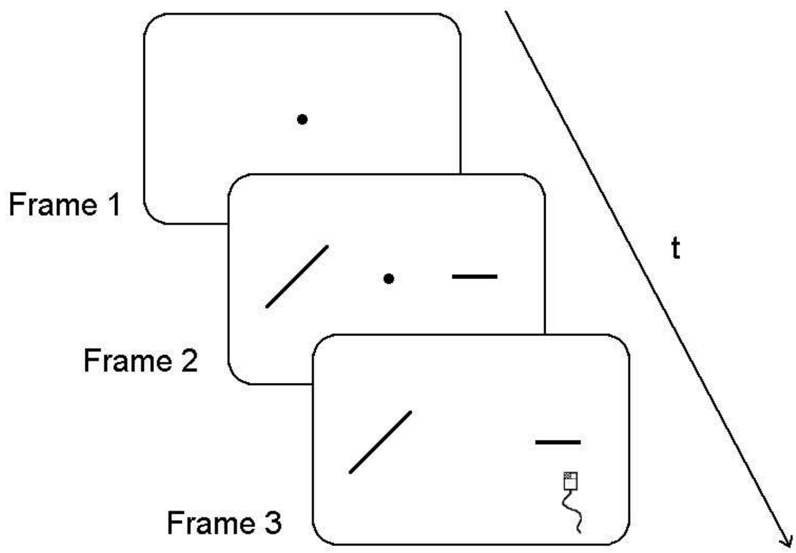


Figure 11.2: The sequence of procedural steps for a trial of Experiment S2. Frame 1: Fixation point. Frame 2: Simultaneous display of target and comparison line segments. Frame 3: Binary decision: Which of the two line segments is longer?

trates the sequence of procedural steps for one trial.

Subjects viewed a total of 180 stimulus pictures during the experiment so that each possible combination of the three target lengths, the three target orientations and the two similarity conditions was displayed ten times. For five of these repetitions, the lengths of the comparison line segments were shorter than the (perceived) target lengths. For the remaining five, the lengths of the comparison line segments were longer than the (perceived) target lengths. The stimulus combinations were presented in random order. Eight practice trials were conducted prior to the experimental trials. The recorded data allowed for the subsequent computation of the reaction time, the discrimination correctness and relevant eye-movement parameters such as the number of fixations, fixation duration or saccade length – and derivatives.

11.3 Results

In comparison with Experiment S1, the procedural design here results in a more complex statistical data analysis. Rather than the previous two-factorial analysis of variance, data is now subjected to a three-factorial analysis of variance in order to account for the three independent variables, namely target line segment length, orientation and, in addition, the discrimination difficulty. The effects of these factors are tested on the dependent variables discrimination correctness DC, the reaction time RT and the same eye-movement parameter that were investigated in Experiment S1. In order to more clearly visualise the differences between the easy and difficult discrimination conditions in the measured dependent variables, line plots will be used instead of the bar charts.

11.3.1 Dependent Variables

Discrimination Correctness DC

Let us first see how subjects “scored”, i.e. how successfully they accomplished their task to correctly identify the longer of the two line segments presented. As the length differences for the easy discrimination condition were set in a pre-experiment (see Section 11.1) in order to yield more than 95% correctness – and thus not allow for much variation – the statistical analysis of DC in the difficult discrimination condition should be of particular interest here.

The analysis of variance confirms the expected effect of the factor discrimination difficulty on the discrimination correctness DC ($F(1;33) = 145.74; p < 0.001$). If data is aggregated over target line segment length and orientation, approximately 99.4% of subjects’ judgements are correct for low line segment length similarity, but only 64.1% when the length similarity is high. The subsequent analysis of the interaction between the discrimination difficulty with either target line segment length ($F(2;66) = 75.01; p < 0.001$) or orientation ($F(2;66) = 33.94; p < 0.001$) yields almost identical results to the respective analyses for the main effects of the factors target length ($F(2;66) = 75.00; p < 0.001$) and orientation ($F(2;66) = 33.93; p < 0.001$). This can be understood when we consider that neither of the two latter factors significantly influences DC in the easy discrimination condition, but does considerably so in the difficult one. Irrespective of target line segment length or orientation the discrimination correctness remains stable between 99% and 100% in the easy discrimination condition.

In contrast, when the two line segment lengths are apparently difficult to distinguish, DC drops from 87.7% for short to 56.9% for intermediate and then to 48.8% for long target lengths. Similarly, DC drops from 85.6% for horizontal to 56.5% for oblique and then to 51.3% for vertical target line segments. As DC remains constant in the easy discrimination condition, independent of the factors target line segment length and orientation, these interactions can also be interpreted as main effects that these two factors exert on DC in the difficult discrimination condition. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences indeed exist between all levels of the factor target line segment lengths: ($R_{crit} = 0.066; p < 0.001$) for short vs. intermediate, ($R_{crit} = 0.083; p < 0.001$) for short vs. long, ($R_{crit} = 0.058; p = 0.019$) for intermediate vs. long target line segments. For the factor target line segment orientation, however, the Newman-Keuls test reveals that significant differences in DC can only be observed between factor levels horizontal and oblique ($R_{crit} = 0.086; p < 0.001$) and between horizontal and vertical ($R_{crit} = 0.107; p < 0.001$), but not between oblique and vertical ($R_{crit} = 0.082; p = 0.200$).

In analogy, the significance of the three-way interaction between the discrimination difficulty, target line segment length and orientation ($F(4; 132) = 4.51; p = 0.003$) is to a large extent due to the difference between the latter two factors when the length discrimination is difficult. The analysis of this two-way interaction, i.e. between target length and orientation, confirms this assumption, yielding almost identical values ($F(4; 132) = 4.52; p < 0.001$). The interaction is obviously caused by considerably more

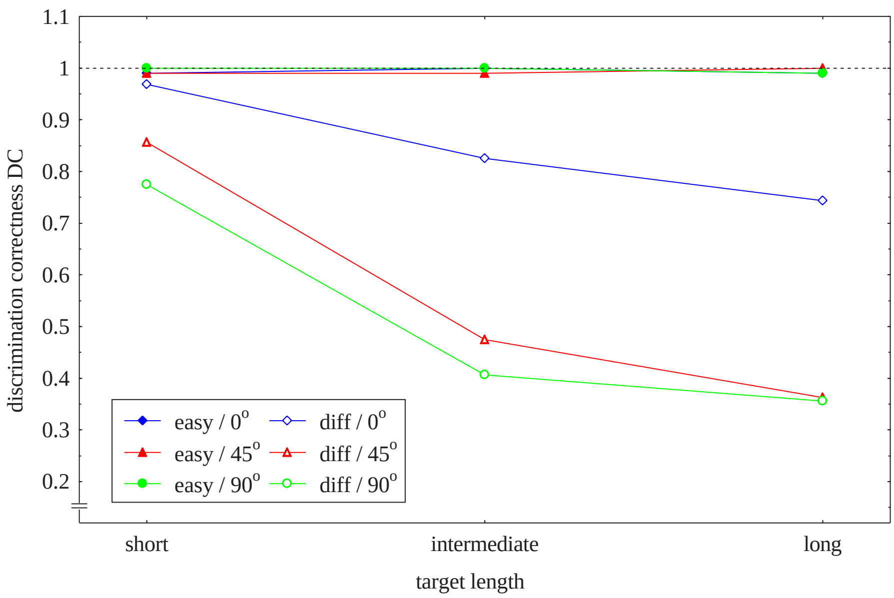


Figure 11.3: Discrimination correctness DC as a function of discrimination difficulty and target line segment orientation for the three possible target lengths.

frequent correct decisions for horizontal target line segments than for those obliquely or vertically oriented. Furthermore, DC does not quite as rapidly decrease from short through intermediate to long target lengths when the target is horizontal. Figure 11.3 illustrates the differences between the easy and difficult discrimination conditions with respect to the discrimination correctness DC for the three target line segment orientations as a function of target line segment length.

After having successfully established that indeed significant differences exist between the discrimination conditions – plus further interactions with target line segment length and orientation – it can be assumed that the analysis of the other dependent variables might yield even more rewarding results. We will consider the more "conventional" variable reaction time RT first.

Reaction Time RT

As previously, we chart the relative frequencies of the reaction time RT in a histogram, based on all measured values for RT, irrespective of target line segment length or orientation, and taking into account the data from all subjects. However, we obtain two curves here: One for the easy and a second for the difficult discrimination condition (see Figure 11.4, left). When the line segment lengths have a low similarity (easy discrimination), RT lies between 385 ms and 3391 ms with an overall mean of 905 ms. This histogram reaches a peak at approximately 590 ms. Approximately 95% of the values lie within the interval of 400 to 1360 ms, the general shape of the distribution could be fitted by an asymmetrical function with positive skewness of +1.72.

The shape of the respective histogram is quite different for line segments that display a high similarity with respect to their lengths (difficult discrimination). Here, a minimum RT of 376 ms and a maximum RT of 17066 ms are measured; the mean reaction time is computed to 1998 ms. This histogram peaks at around 1500 ms. Approximately 95% of the values lie within the interval of 700 to 3500 ms and the distribution could be fitted by an asymmetrical function with positive skewness of +3.22.

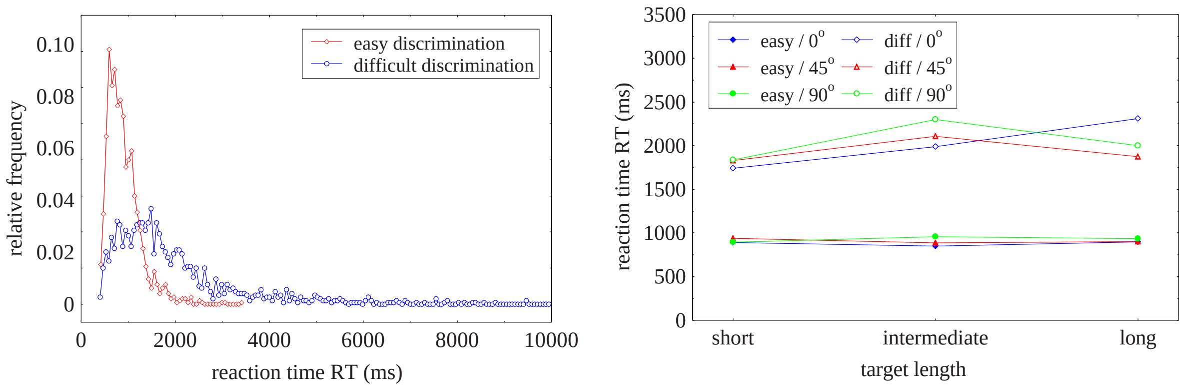


Figure 11.4: Left: Cumulative relative frequency distributions of reaction times RT over all target line segment lengths and orientation levels, separated for the easy (red) and difficult (blue) discrimination conditions. Right: Reaction time RT as a function of discrimination difficulty and target line segment orientation for the three possible target lengths.

The analysis of variance yields a significant main effect on RT for the factor discrimination difficulty ($F(1;33) = 41.20; p < 0.001$) (means: See above). RT also significantly varies with target line segment length ($F(2;66) = 5.84; p = 0.007$). When the target line segment is short, subjects on average require 1354.3 ms to assess its length. For intermediate and long target lengths, RT increases to 1513.9 ms and to 1486.3 ms, respectively. The post-hoc comparison of means using the Newman-Keuls test reveals that significant differences only exist between short and intermediate ($R_{crit} = 129.7; p = 0.019$) and between short and long line segments ($R_{crit} = 112.2; p = 0.024$), but not between intermediate and long line segments ($R_{crit} = 67.5; p = 0.397$). The third factor target line segment orientation does not exert a significant main effect on RT ($F(2;66) = 0.98; p = 0.387$), RT only slightly varies between 1445.6, 1422.3 and 1486.5 ms for the three target orientations 0^o, 45^o and 90^o, respectively.

Apart from these main effects, only the interaction between target line segment length and orientation reaches significance ($F(4;132) = 3.28; p = 0.017$). This must be attributed to the steadily increasing RT for horizontally oriented target line segments over target lengths (1314.7, 1418.6, 1603.7 ms for short, intermediate and long target line segments) – in contrast to the curves for the obliquely (1383.1, 1496.1, 1387.1 ms) and vertically (1364.3, 1627.0, 1468.1 ms) oriented ones that peak for intermediate lengths.

The observed dependences are visualised in Figure 11.4 (right) where RT is displayed as a function of discrimination difficulty and target line segment orientation for the three possible target lengths.

Analysis of Eye-Movement Data: Preliminaries

The analyses of the relevant eye-movement parameters will be conducted here in analogy to Experiment S1. This in particular means that measures such as the number of fixations NF or fixation duration FD will be analysed both globally – averaged over the whole stimulus display – and locally – within specific spatial display regions that we consider potentially relevant for the solution of the discrimination task.

Again, we divide the space into two sections surrounding the line segments and an intermittent section for which separate analyses for NF and, in the following paragraphs, for the other eye-movement parameters will be computed. The sizes of these sections are set according to the previous specifications (see Section 10.2.1, paragraph "Analysis of Eye-Movement Data: Preliminaries") and subsequently validated using the same cluster-analysis method (k-means algorithm). As before, the comparison of the clustering and the definition of sections yields very little divergence. On average, this ratio of inconsistently assigned fixations measures only 0.3%. We can thus assume that the "sectioning" presents a plausible basis for the subsequent computation of local eye-movement parameters in Experiment S2 as well.

Figures 11.5 and 11.6 illustrate the distributions for all possible combinations of target line segment lengths and orientations. Figure 11.5 shows these distributions for the easy discrimination condition, Figure 11.6 for the difficult one.

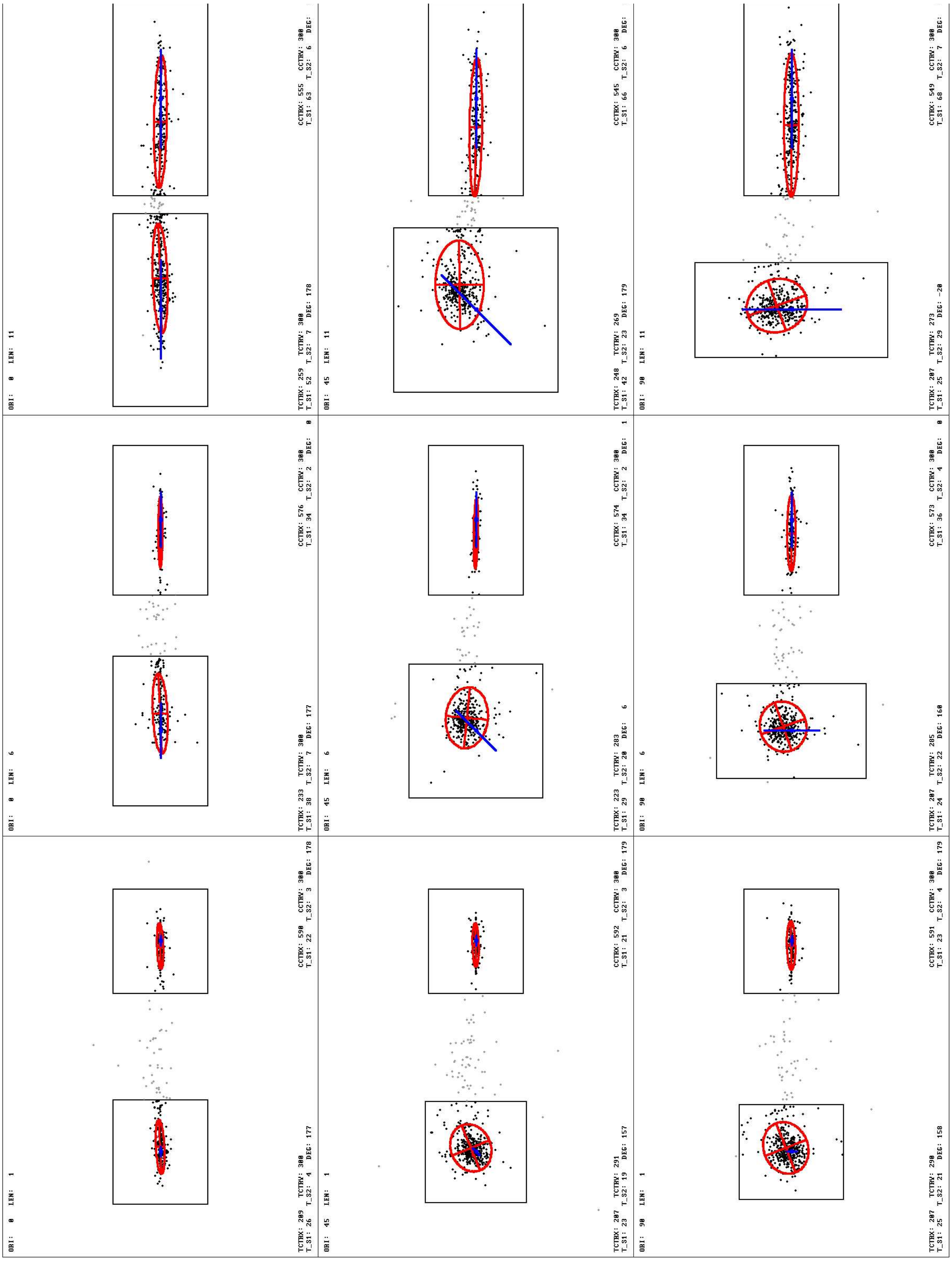


Figure 11.5: Distribution of the fixation points for all possible combinations of target line segment lengths and orientations, aggregated over all subjects for the easy discrimination condition.

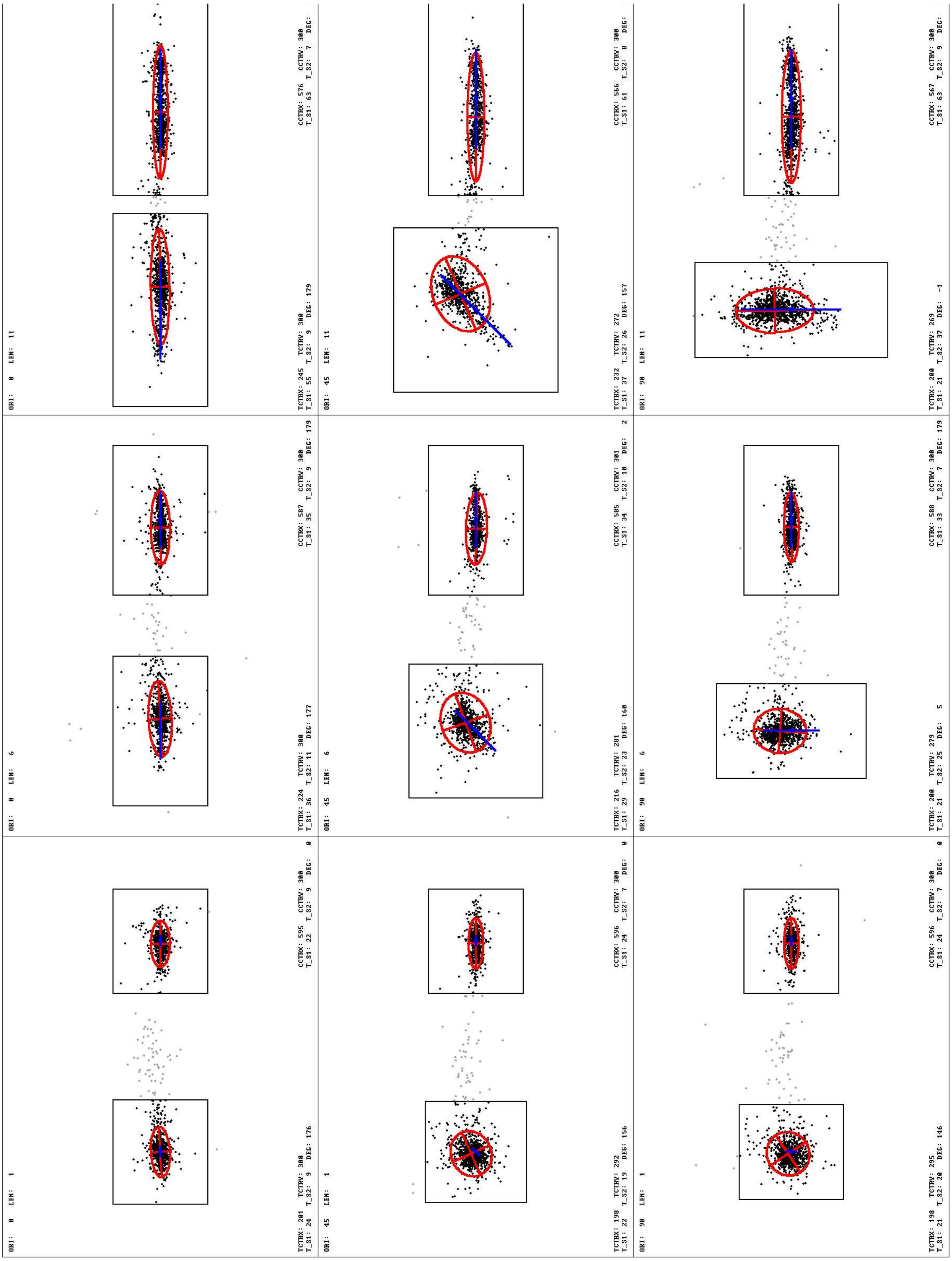


Figure 11.6: Distribution of the fixation points for all possible combinations of target line segment lengths and orientations, aggregated over all subjects for the difficult discrimination condition.

Number of Fixations NF

In analogy to Experiment S1, separate measures for the numbers of fixations are defined: NF_T and NF_C for fixations that occur in proximity to the target and the comparison stimuli, respectively, and NF_I for intermittent fixations that occur between the two stimuli. To start with, a separate analysis of the overall number of fixations NF is computed and investigated as to possible effects of the independent variables discrimination difficulty, target line segment length and orientation.

The analysis of variance reveals significant main effects for all factors. In detail, the analysis yields ($F(1;33) = 71.98; p < 0.001$) for the effect of the discrimination difficulty on NF. If data is summarised over the remaining two factors, subjects on average fixate only 2.48 times on the whole display before making their decision in case the two line segments are of low length similarity, but 5.58 fixations in case of high similarity, i.e. NF more than doubles.

The effect of target line segment length on NF also reaches significance ($F(2;66) = 8.70; p < 0.001$). On average, subjects fixate 3.91 times on the whole stimulus display during the assessment of a short target line segment. When the target line segment has intermediate length, the overall number of fixations NF is 3.82 and rises to 4.36 for long targets. Although the interaction between target line segment length and the discrimination difficulty does not reach a significant level ($F(2;66) = 1.51; p = 0.228$), it must be noted that, for the difficult discrimination condition, NF constantly rises from 5.35 through 5.45 to 5.94 fixations with increasing target length whereas for the easy discrimination condition, this is not the case. Here, NF drops from 2.47 for short to 2.19 for intermediate target lengths and only then increases to 2.77 fixations. These – at first sight – contradicting observations can be understood when taking into account the results of a post-hoc comparison of means. Specifically, the Newman-Keuls test demonstrates that no significant differences exist in NF between short and intermediate target line segments in either the easy or difficult discrimination condition. Thus, the contrary slopes do not affect the analysis of variance, i.e. they do not cause a significant interaction effect for the two factors discrimination difficulty and target line segment length.

The third main effect, namely that of target line segment orientation on the overall NF, is a significant one as well ($F(2;66) = 4.20; p = 0.019$). Average NF is computed to 4.06 fixations when the target line segments are oriented horizontally, to 3.82 when oriented obliquely and to 4.20 when oriented vertically. Here, these "steps" between the different orientation levels are maintained when data is analysed for the two discrimination difficulties separately. For the easy discrimination condition, NF measures 2.49, 3.25 and 2.59 fixations for the three orientations, for the difficult condition 5.64, 5.29 and 5.81, respectively.

All two- and three-way interactions between discrimination difficulty, target line segment length and orientation do not reach significance. Figure 11.7 graphically illustrates the relevant mean values for NF as a function of target line segment length and orientation for the two discrimination levels.

Next, we will check how the local numbers of fixations NF_T, NF_C and NF_I, i.e. those

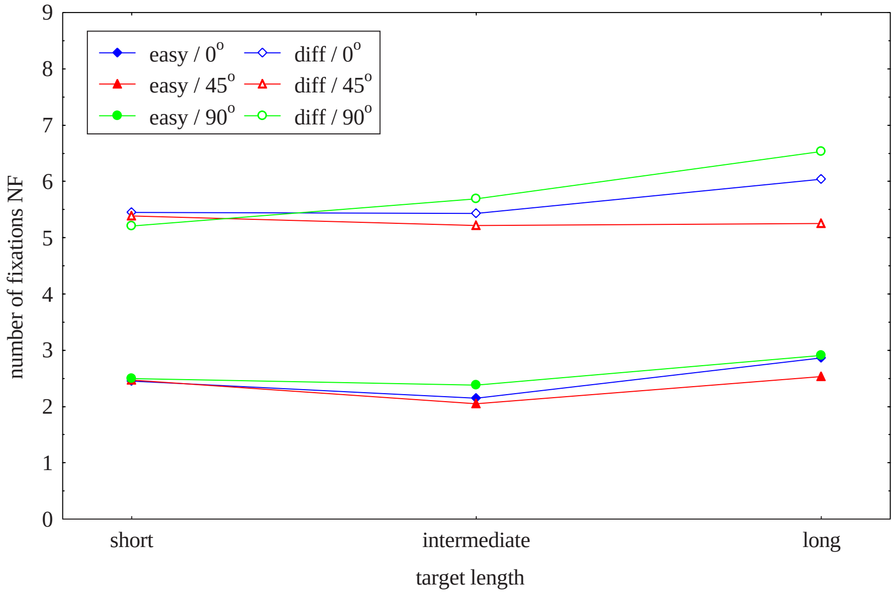


Figure 11.7: Overall number of fixations NF as a function of target line segment length, separated for the three target orientations. The three line plots in the lower field of the graph illustrate NF for the easy discrimination condition, those in the upper field for the difficult one.

in the target and comparison hemifields and that in the intermittent display section, are affected by the factors discrimination difficulty, target line segment length and orientation.

The first analysis shows that NF_T is significantly influenced only by the factors discrimination difficulty ($F(1;33) = 75.58; p < 0.001$) and target line segment length ($F(2;66) = 3.66; p = 0.031$). On average, subjects fixate the target section of the stimulus display 1.27 times when the discrimination is easy. Like NF, NF_T more than doubles when the two line segment lengths are difficult to distinguish and measures 2.79 fixations. Although the effect of target line segment length on NF_T reaches significance (see above), absolute differences between the target length levels are rather small – 1.98 fixations in the target section for short, 1.96 for intermediate and 2.14 for long targets. Furthermore, a Newman-Keuls test confirms that significant differences exist between short and long ($R_{crit} = 0.157; p = 0.028$) and intermediate and long target length levels ($R_{crit} = 0.127; p = 0.046$), but not between short and intermediate levels ($R_{crit} = 0.133; p = 0.841$). Separated by discrimination difficulty, NF_T measures 1.27, 1.16 and 1.39 fixations for the three target lengths short, intermediate and long in the easy discrimination condition, in the difficult condition 2.70, 2.78 and 2.89, respectively. The main effect of the factor target line segment orientation on NF_T ($F(2;66) = 1.87; p = 0.163$) and all two- and three-way interactions between discrimination difficulty, target line segment length and orientation do not reach significance. Figure 11.8 (top left) graphically illustrates the relevant mean values for NF_T as a function of target line segment length and orientation for the two discrimination levels.

Similar effects of the factors discrimination difficulty, target line segment length and orientation can be found on NF_C, i.e. the number of fixations that occur in proximity to the comparison line segment. Discrimination difficulty ($F(1;33) = 70.78; p < 0.001$)

and target length ($F(2;66) = 17.20; p < 0.001$) exert a highly significant effect on NF_C, whereas target orientation does not ($F(2;66) = 3.91; p = 0.063$) – but shows a tendency towards a corresponding effect. As before, differences are most clearly visible between the easy and difficult discrimination levels, NF_C is computed to 1.09 fixations in case of low length similarity and to 2.65 when length similarity is high. The absolute values of the differences between the target length levels are relatively small: 1.75 for short, 1.73 for intermediate and 2.13 fixations in the comparison section for long target line segments. When separated for the two discrimination conditions, NF_C measures 1.05, 0.93 and 1.29 (easy) and 2.46, 2.53 and 2.97 (difficult) for the possible target lengths, respectively. The post-hoc comparison of means using the Newman-Keuls test confirms the assumption that the significance of the effect of target line segment length on NF_C is due to significant differences between the short and long ($R_{crit} = 0.172; p < 0.001$) and the intermediate and long ($R_{crit} = 0.161; p < 0.001$), but not between the short and intermediate target length levels ($R_{crit} = 0.133; p = 0.708$). Again, all two- and three-way interactions between discrimination difficulty, target line segment length and orientation do not reach significance. The mean values of NF_C are charted in Figure 11.8 (top right) as a function of target line segment length and orientation for the two discrimination

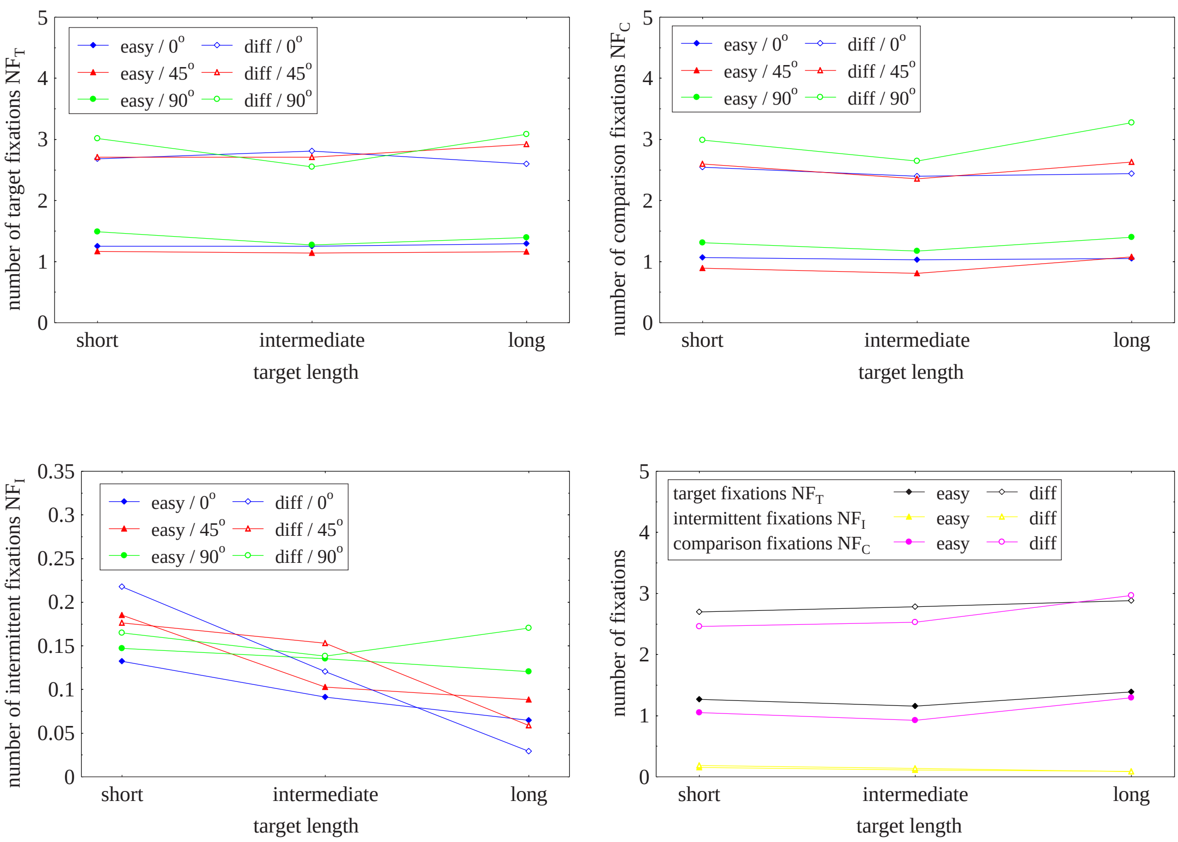


Figure 11.8: Local numbers of fixations in the target (NF_T, top left), the comparison (NF_C, top right) and the intermittent (NF_I, bottom left) sections as a function of target line segment length and orientation for the easy and difficult discrimination conditions. Bottom right: Comparison of the local numbers of fixations in the target (NF_T), intermittent (NF_I) and comparison (NF_C) sections as a function of target line segment length and discrimination difficulty. (N.B.: Different vertical scale used for NF_I)

levels.

The statistical analysis of the number of intermittent fixations NF_I that occur in the area between the two stimuli yields rather different results compared to those obtained in the previous analyses of the NFs. Specifically, now all main effects reach significance. A detailed analysis of means reveals that again only very few fixations fall within the intermittent section, NF_I is computed to 0.19 in case of an easy discrimination and to 0.14 in case of a difficult one, yielding a significant main effect of the discrimination difficulty on NF_I ($F(1;33) = 4.45; p = 0.043$). In other words, on average intermittent fixations only occur between every seventh and ninth trial. If we further consider that, overall, more than twice as many fixations (NF_I) occur when the discrimination task is a difficult one – compared to the easy discrimination condition – it must be noted that these intermittent fixations account for approximately 2% of all fixations in case of a difficult discrimination, but for approximately 4% in case of an easy one.

The comparison of means also yields that significantly fewer intermittent fixation occur the longer the target line segment becomes ($F(2;66) = 15.32; p < 0.001$): 0.17 fixations for short targets, 0.12 for intermediate and 0.09 for long ones – with differences between all target length levels being significantly different from each other, according to a Newman-Keuls post-hoc test: ($R_{crit} = 0.034; p = 0.002$) for the comparison between short and intermediate targets, ($R_{crit} = 0.030; p < 0.001$) for the comparison between short and long targets and ($R_{crit} = 0.025; p = 0.022$) for the comparison between intermediate and long targets.

Finally, the factor target length orientation exerts a significant main effect on the dependent variable NF_I ($F(2;66) = 6.11; p = 0.004$). On average 0.11 intermittent fixations occur when the target is oriented horizontally, 0.13 when it is oblique and 0.15 when vertical. The post-hoc comparison of means, however, yields that only the difference between horizontal and vertical target line segments accounts for this significant main effect ($R_{crit} = 0.023; p = 0.003$), whereas the other factor levels do not: ($R_{crit} = 0.019; p = 0.089$) for the comparison between horizontal and oblique and ($R_{crit} = 0.022; p = 0.081$) for the comparison between oblique and vertical. The two- and three-way interactions between discrimination difficulty, target line segment length and orientation do not reach significance. Figure 11.8 (bottom left) charts the mean NF_I for the possible factor combinations.

In order to check if significant differences exist between NF_T, NF_C and NF_I an enhanced analysis of variance is computed. As introduced in Experiment S1, it tests in particular for the effects of the additional factor "section" on the number of fixations with factor levels being the target, comparison and intermittent fixation sections. Indeed, the analysis confirms the assumed significant effect of the fixation section on the number of fixations ($F(2;66) = 185.88; p < 0.001$). However, the Newman-Keuls test reveals that significant differences only exist between NF_T and NF_I ($R_{crit} = 0.257; p < 0.001$) and between NF_C and NF_I ($R_{crit} = 0.262; p < 0.001$) – which could have been expected. In contrast to the findings of the "dynamic" Experiment S1, no significant differences exist between NF_T and NF_C ($R_{crit} = 0.115; p = 0.156$). Figure 11.8 (bottom right) visualises these dependences. NF_T, NF_C and NF_I are displayed in direct comparison for the three possible target lengths and the easy and difficult discrimination conditions. As target line segment orientation does not exert a significant effect on NF_T and NF_C and in order to improve clarity of the chart, data is aggregated over this factor.

Fixation Duration FD

Separate analyses are also computed for the overall fixation duration FD and its local equivalents FD_T, FD_C and FD_I, i.e. the fixation durations within the target, the comparison and the intermittent stimulus display section, respectively.

Let us start examining the overall fixation duration FD. The analysis of variance yields a significant main effect of the factor discrimination difficulty on FD ($F(1;33) = 42.77; p < 0.001$). The comparison of means for the two factor levels shows that subjects on average fixate 215.91 ms when the line segment length similarity is low, but that fixations are prolonged by approximately 15% and last 247.63 ms when the length similarity is high. We further observe that FD increases for long target line segments (249.42 ms), compared to short (233.78 ms) and intermediate ones (212.1 ms). This constitutes a highly significant effect of the factor target line segment length on FD ($F(2;66) = 15.94; p < 0.001$). No significant effect of target line segment orientation is found ($F(2;66) = 0.35; p = 0.704$). FD remains almost constant at approximately 231 ms, irrespective of the target orientation.

The only interaction effect to reach a significant level is that between the discrimination difficulty and target length ($F(2;66) = 11.38; p < 0.001$). When we consider FD separately for the two discrimination conditions, their means show an increase in FD from short through intermediate to long target lengths – as found when we established the significant main effect of target length on FD (see above) – only when the discrimination is easy. In this case the overall fixation duration rises from 192.36 ms for short through 210.22 ms for intermediate to 245.17 ms for long target line segments. When the two line segment lengths are difficult to discriminate, FD significantly increases only from short (231.88 ms) to intermediate target lengths (257.34 ms), but then remains on that FD level for long lengths (253.68 ms). This is confirmed by a post-hoc comparison of means using the Newman-Keuls test: ($R_{crit} = 11.539; p < 0.001$) for differences between short and intermediate target line segment length, ($R_{crit} = 13.836; p = 0.003$) for differences between short and long ones and ($R_{crit} = 10.748; p = 0.494$) for differences between intermediate and long ones. All other two- and three-way interactions between the factors do not reach significance. Figure 11.9 charts the mean values for NF as a function of target line segment length and orientation for the two discrimination conditions.

In addition, separate analyses are computed for the local fixation durations FD_T, FD_C and FD_I. The analysis of variance yields a significant main effect for the factor discrimination difficulty on FD_T ($F(1;33) = 58.66; p < 0.001$). The average FD_T is computed to 209.21 ms for the easy discrimination condition and increases to 244.68 ms for the difficult condition. Furthermore, fixations in proximity to the target line segment location last 213.11 ms, 231.30 ms and 236.42 ms for short, intermediate and long targets, respectively. An analysis of variance demonstrates that the factor target line segment length has a significant effect on FD_T ($F(2;66) = 14.90; p < 0.001$). However, as

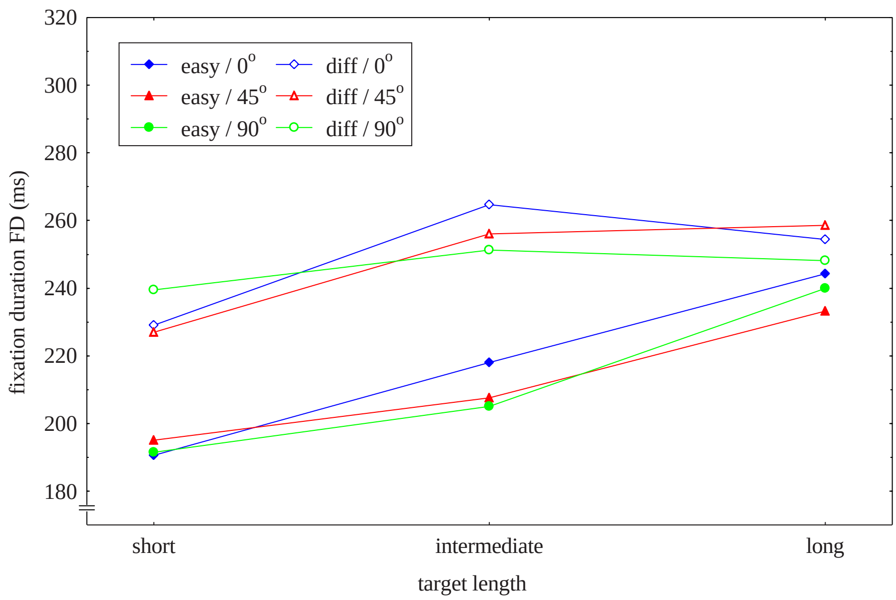


Figure 11.9: Average global fixation duration FD as a function of target line segment length, separated for the three target orientations and the two discrimination conditions.

can be suspected from the differences between the means for the three target lengths, this effect originates from significant differences in FD_T between short and intermediate and between short and long target line segments only. The corresponding results of the Newman-Keuls test produced ($R_{crit} = 9.306; p < 0.001$) and ($R_{crit} = 7.869; p < 0.001$) for those two comparisons, but ($R_{crit} = 10.055; p = 0.308$), i.e. no significant effect, for the comparison between intermediate and long targets. A closer inspection of the FD_T means reveals that considerable differences exist between FD_T when separated for the two discrimination conditions. Analogous to the findings for the overall fixation duration FD, these differences are indeed significant, as the significance level of the interaction between the factors discrimination difficulty and target line segment length proves ($F(2; 66) = 4.83; p = 0.011$). Whereas FD_T significantly increases between all target length levels when the length discrimination is easy (short: 191.98 ms; intermediate: 209.39 ms; long: 226.27 ms), FD_T does not in case the discrimination is difficult (short: 234.23 ms; intermediate: 253.22 ms; long: 246.58 ms). Here, a significant increase in FD_T can only be found between short and intermediate ($R_{crit} = 12.809; p = 0.005$) and short and long target line segments ($R_{crit} = 13.581; p = 0.021$), but not between intermediate and long ones ($R_{crit} = 10.811; p = 0.221$), according to a Newman-Keuls post-hoc test.

Neither the main effect of the factor target orientation nor any other two- or three-way interaction of the three factors discrimination difficulty, target line segment length and orientation reaches significance. Figure 11.10 (top left) visualises all means for FD_T for the two discrimination difficulties and the three possible target orientations as a function of target length.

Taking into account that the comparison between the number of fixations in the target and comparison sections, NF_T and NF_C, respectively, did not result in statistically significant differences, it might be assumed that similar correlations exists regarding FD_T

and FD_C. Indeed, the analysis of variance for FD_C and the comparison of means seem to confirm this assumption; results and effects very closely resemble those obtained for FD_T. In detail, we can establish a significant main effect of the factors discrimination difficulty ($F(1;33) = 62.50; p < 0.001$) and target line segment length ($F(2;66) = 9.74; p < 0.001;$) on FD_C. Average FD_C is 231.11 ms for the easy discrimination condition and increases to 267.09 ms for the difficult condition. Fixations in proximity to the comparison line segment location last 225.98 ms, 254.92 ms and 266.40 ms for short, intermediate and long targets, respectively. Analogous to the analysis of FD_T, a post-hoc comparison of means using the Newman-Keuls test demonstrated that this effect originates from significant differences in FD_C between short and intermediate ($R_{crit} = 10.242; p < 0.001$) and between short and long target line segments ($R_{crit} = 22.941; p = 0.001$) only. The test produced no significant effect for the comparison between intermediate and long targets ($R_{crit} = 21.704; p = 0.290$).

Neither the main effect of the factor target orientation nor most two- or three-way interactions of the three factors discrimination difficulty, target line segment length and orientation reach significance. Only the interaction between the factors discrimination difficulty and target line segment length yields a significant two-way interaction effect on

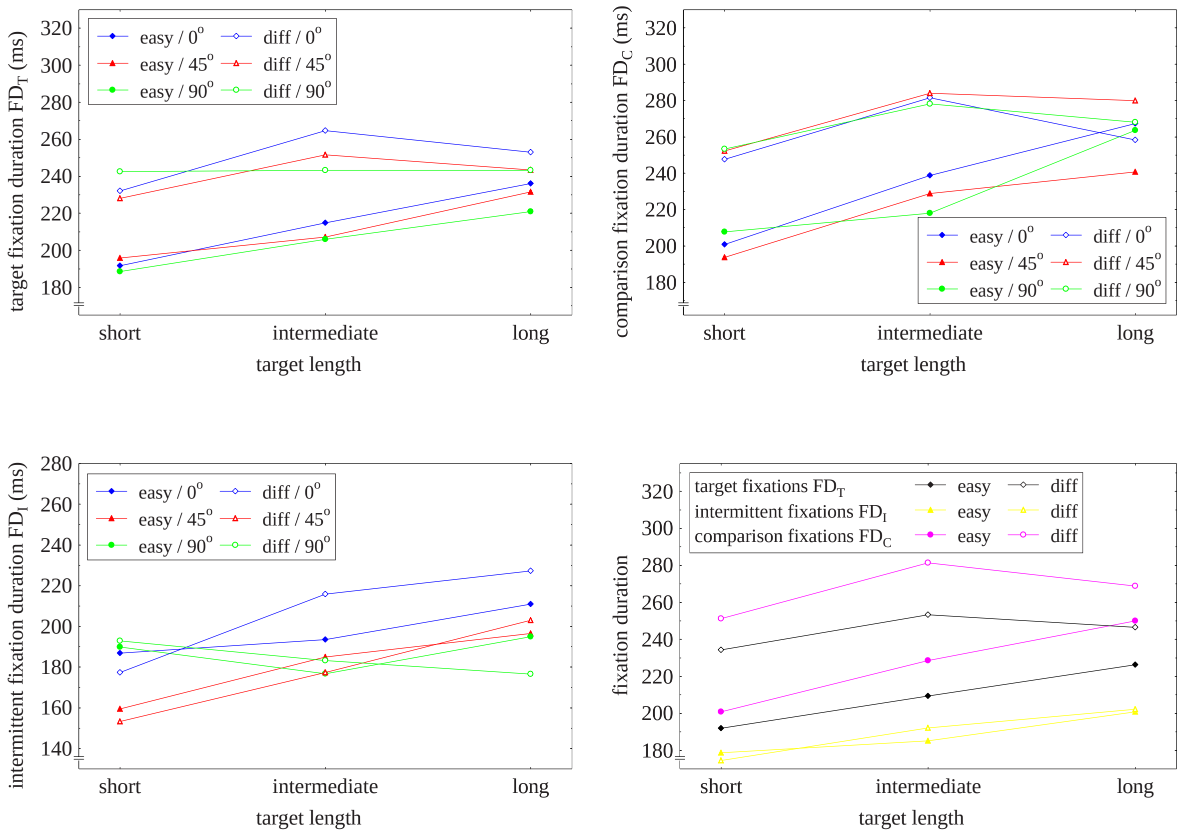


Figure 11.10: Local fixation durations in the target (FD_T, top left), the comparison (FD_C, top right) and the intermittent (FD_I, bottom left) sections as a function of target line segment length and orientation for the easy and difficult discrimination conditions. Bottom right: Comparison of the local fixation duration in the target (FD_T), intermittent (FD_I) and comparison (FD_C) sections as a function of target line segment length and discrimination difficulty.

FD_C ($F(2;66) = 14.12; p < 0.001$), reflecting considerable differences between FD_C for short, intermediate and long targets when separated for the two discrimination conditions. Whereas FD_C significantly increases between all target length levels when the length discrimination is easy (short: 200.82 ms; intermediate: 228.56 ms; long: 263.94 ms), FD_C does not when the discrimination is difficult (short: 251.15 ms; intermediate: 281.27 ms; long: 268.85 ms). Here, a significant increase in FD_C can only be found between short and intermediate ($R_{crit} = 15.342; p < 0.001$) and short and long target line segments ($R_{crit} = 19.452; p = 0.050$), but not between intermediate and long ones ($R_{crit} = 15.729; p = 0.118$), according to a Newman-Keuls post-hoc test. Figure 11.10 (top right) visualises all means for FD_C for the two discrimination difficulties and the three possible target orientations as a function of target length.

Finally, the investigation of the duration of intermittent fixation, FD_I, completes the statistical analysis of FDs. The comparison of means yields almost identical average fixation durations for both discrimination conditions, about 188.82 ms. Consequently, the analysis of variance does not produce a significant main effect for the factor discrimination difficulty ($F(1;33) = 0.09; p = 0.767$). As for FD_T and FD_C, the factor target line segment length exerts a significant effect on FD_I ($F(2;66) = 7.14; p = 0.002$) and yields means that increase from 176.62 ms for short through 188.63 ms for intermediate to 201.54 ms for long targets. The analysis of variance also reveals a significant main effect of the factor target line segment orientation on FD_I ($F(2;66) = 7.52; p = 0.002$). As the means for the different orientation levels suggest – 201.99 ms for horizontal targets, 179.12 ms for oblique and 185.69 ms for vertical ones – the significance of this effect has to be attributed to the significant differences between the factor levels horizontal and oblique ($R_{crit} = 12.146; p < 0.001$) and horizontal and vertical ($R_{crit} = 13.297; p = 0.018$), whereas the Newman-Keuls test cannot establish significance for the difference between oblique and vertical target orientation levels ($R_{crit} = 11.505; p = 0.254$). None of the two- and three-way interactions between the factors reach significance. Figure 11.10 (bottom left) charts the mean NF_I for the possible factor combinations.

Although results obtained for the statistical analyses of FD_T and FD_C are very similar (see above) and do not seem to suggest significant differences between the sections with regard to the fixation duration, a final "comparative" analysis is being computed as before. It tests in particular for the effects of the additional factor "section" on the fixation duration with factor levels being the target, comparison and intermittent fixation sections. Indeed, the analysis confirms the assumed significant effect of the fixation section on the number of fixations ($F(2;66) = 26.80; p < 0.001$), the mean fixation time is 226.94 ms in the target section, 249.10 ms in the comparison and only 188.93 ms in the intermittent one. Contrary to the earlier expectation that no significant differences exist between FD_T and FD_C, the Newman-Keuls test reveals significant differences between all levels of the factor section. It yields ($R_{crit} = 18.412; p = 0.020$) between FD_T and FD_C, ($R_{crit} = 17.359; p < 0.001$) between FD_T and FD_I and ($R_{crit} = 14.677; p < 0.001$) between FD_C and FD_I. Figure 11.10 (bottom right) visualises these dependences, FD_T, FD_C and FD_I are displayed in direct comparison for the three possible target lengths and the easy and difficult discrimination conditions. As target line segment orientation does not exert a significant effect on FD_T and FD_C and in order to improve clarity of the chart, data is aggregated over this factor.

Number of Saccades between Hemifields SB

As in Experiment S1 previously, we consider the number of saccades between the two stimulus hemifields SB as the last more "global" measure. The analysis of variance yields a significant main effect for the factor discrimination difficulty ($F(1;33) = 107.64; p < 0.001$). SB significantly increases from only 1.79 for the easy discrimination condition to 3.55 for the difficult one. The effects of both target line segment length ($F(1;33) = 8.05; p = 0.001$) and orientation ($F(2;66) = 5.22; p = 0.008$) on SB also reach significance, however, differences between the individual levels of these two factors are less pronounced. When targets are short, average SB measures 2.59, when intermediate 2.77 and when vertical 2.81. As the post-hoc comparison of means shows (Newman-Keuls test), a significant increase can only be observed for the SB differences between short and intermediate ($R_{crit} = 0.130; p = 0.007$) and between short and long targets ($R_{crit} = 0.127; p = 0.002$), but not between intermediate and long targets ($R_{crit} = 0.092; p = 0.486$). More specifically, separated by the discrimination difficulty, SB is 1.77, 1.88 and 2.02 for short, intermediate and long target line segments when the discrimination is easy and 3.41, 3.66 and 3.59 when the discrimination is difficult. For horizontal, oblique and vertical targets, the average SB is computed to 2.77, 2.62 and 2.78, respectively. According to the Newman-Keuls post-hoc test, the significant main effect has to be attributed to significant differences in SB between horizontal and oblique ($R_{crit} = 0.073; p < 0.001$) and between vertical and oblique targets ($R_{crit} = 0.130; p = 0.023$), but not between horizontal and vertical targets ($R_{crit} = 0.118; p = 0.947$). No significant interactions between discrimination difficulty, target line segment length and/or orientation can be observed.

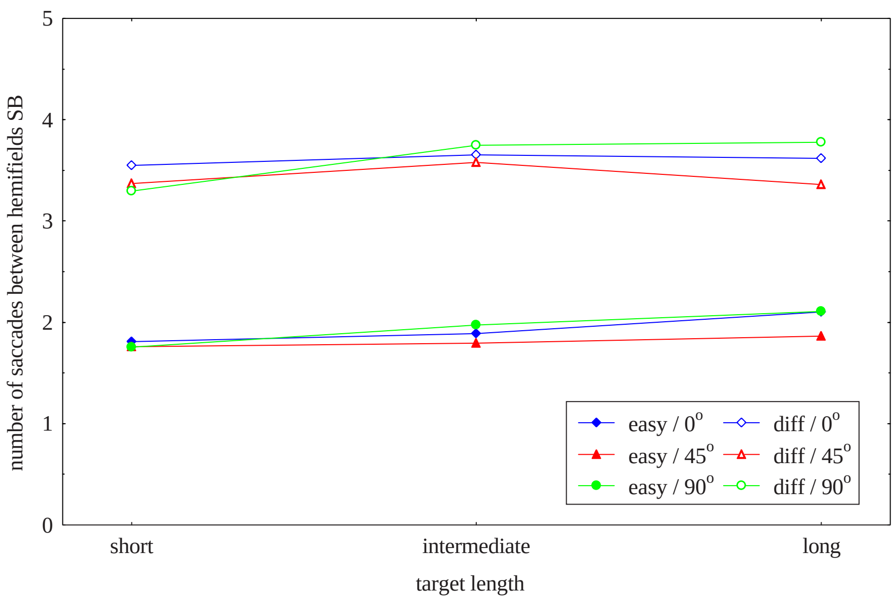


Figure 11.11: Number of saccades between stimulus hemifields SB as a function of target line segment length and orientation, separated for the two discrimination difficulties.

The detailed SB means for the combinations of discrimination difficulties, target lengths and orientations are charted in Figure 11.11.

Number of Successive Fixations within the same Hemifield FW

As argued in Experiment S1, the analysis of the number of successive fixations within the same hemifield will be considered in the target (FW_T) and comparison (FW_C) sections, i.e. hemifields, only. With the number of fixations NF_I being considerably below one in the intermittent stimulus display section, a sensible sequence of fixations for that region cannot be constituted in Experiment S2 either. FW_I can thus be excluded from the analysis. In addition to FW_T and FW_C, an overall FW, averaging over both hemifields, will be analysed again first.

The analysis of variance for FW yields significant main effects for all factors. The effect for the discrimination difficulty is computed to ($F(1;33) = 124.75; p < 0.001$) and manifested in a mean FW of 1.56 for the easy discrimination condition and 2.18 for the difficult one. FW also significantly varies with target line segment length ($F(2;66) = 11.86; p < 0.001$). Mean FW measures 1.82 for short target segments, remains almost unchanged for intermediate ones (1.79) and then rises to 2.00 fixations for long ones. As expected, the Newman-Keuls post-hoc test confirms the significant differences between the target length level short and long ($R_{crit} = 0.110; p = 0.003$) and intermediate and long ($R_{crit} = 0.077; p < 0.001$), but not between short and intermediate ($R_{crit} = 0.090; p = 0.502$). Separated for the two discrimination levels, FW is 1.52, 1.45 and 1.71 for short, intermediate and long targets when the line segments have a low length similarity and 2.12, 2.14 and 2.29 when the length similarity is high.

Finally, the target line segment orientation also exerts a significant main effect on FW ($F(2;66) = 5.36; p = 0.007$). With FW being identical when the target is oriented either horizontally or obliquely (1.84), it does not come as a surprise that the Newman-Keuls test only classifies the differences between these two orientation levels and the vertical level – where FW is 1.93 – as statistically significant and being responsible for the significance of the main effect. More specifically, the test yields ($R_{crit} = 0.058; p = 0.976$) for the difference between the orientation factor levels horizontal and oblique, ($R_{crit} = 0.058; p = 0.004$) for the difference between horizontal and vertical and ($R_{crit} = 0.075; p = 0.021$) for the difference between oblique and vertical. Separated for the two discrimination levels, FW is 1.53, 1.53 and 1.62 for horizontal, oblique and vertical targets when the line segments have a low length similarity and 2.16, 2.15 and 2.24 when the length similarity is high. None of the two- or three-way interactions reaches significance. Figure 11.12 visualises the means for the number of successive fixations within the same hemifield FW for the three target orientations and the discrimination difficulty as a function of target line segment length.

Let us next consider the number of successive fixations within the target FW_T and comparison FW_C hemifields. A separate analysis of variance for FW_T results in significant main effects for all factors discrimination difficulty ($F(1;33) = 57.44; p < 0.001$), target line segment length ($F(2;66) = 57.44; p = 0.006$) and orientation ($F(2;66) = 6.17; p =$

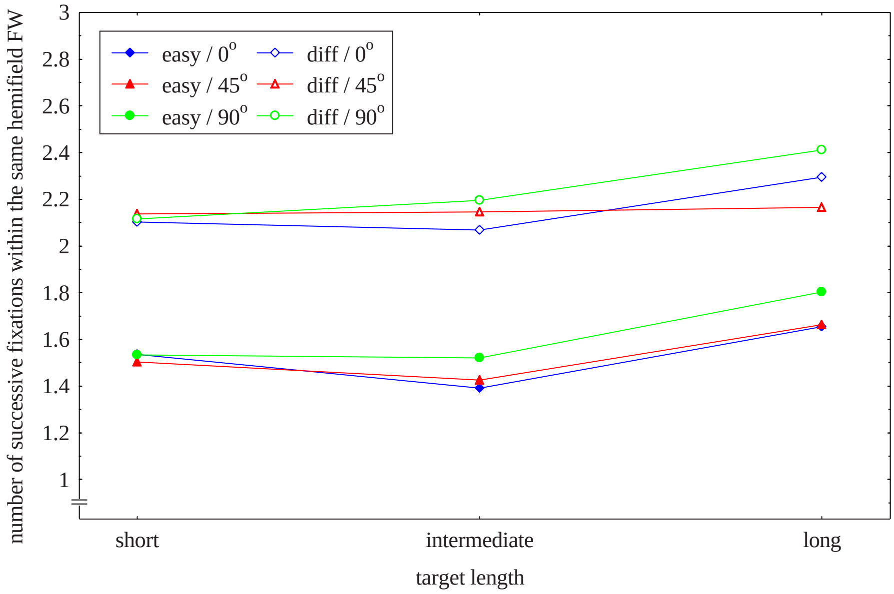


Figure 11.12: Average number of successive fixations within the same hemifield FW – either in the target or the comparison hemifield – as a function of target line segment length, separated for the three target orientations and the discrimination difficulty.

0.003); none of the interactions reaches significance. Whereas subjects only successively fixate 1.85 times within the target hemifield when the comparison is easy, they execute 2.35 successive fixations in case of a difficult length discrimination. The significant variation of FW_T with target length is manifested in means that increase from 2.02 to 2.07 and further to 2.22 successive fixations for short, intermediate and long target line segments, respectively. The usual post-hoc comparison of means using the Newman-Keuls test again shows that not all differences between the lengths levels significantly differ from each other, but only those between the short and long ($R_{crit} = 0.151; p = 0.011$) and between the intermediate and long levels ($R_{crit} = 0.103; p = 0.005$). FW_T does not significantly differ when we compare the means between short and intermediate targets ($R_{crit} = 0.120; p = 0.434$). Separated for the two discrimination conditions, FW_T measures 1.78, 1.77 and 2.00 for short, intermediate and long targets, respectively, in case the discrimination is easy and 2.26, 2.35 and 2.43 otherwise. When FW_T is investigated dependent on the target orientation, the means increase significantly from 2.00 successive fixations for horizontally oriented targets to 2.14 for oblique ones ($R_{crit} = 0.104; p = 0.009$) and further to 2.16 for vertical ones. The Newman-Keuls post-hoc test does not classify the latter difference as being significant ($R_{crit} = 0.107; p = 0.668$), whereas the one between horizontal and vertical orientation levels reaches significance ($R_{crit} = 0.097; p = 0.002$). In further detail, FW_T measures 1.76, 1.89 and 1.91 for the three target orientations, respectively, when the discrimination difficulty is easy. In the difficult discrimination condition, FW_T is 2.24, 2.39 and 2.42. Figure 11.13 (left) visualises the means for the number of successive fixations within the target hemifield FW_T for the three target orientations and the discrimination difficulty as a function of target line segment length.

The number of successive fixations within the comparison hemifield FW_C must be

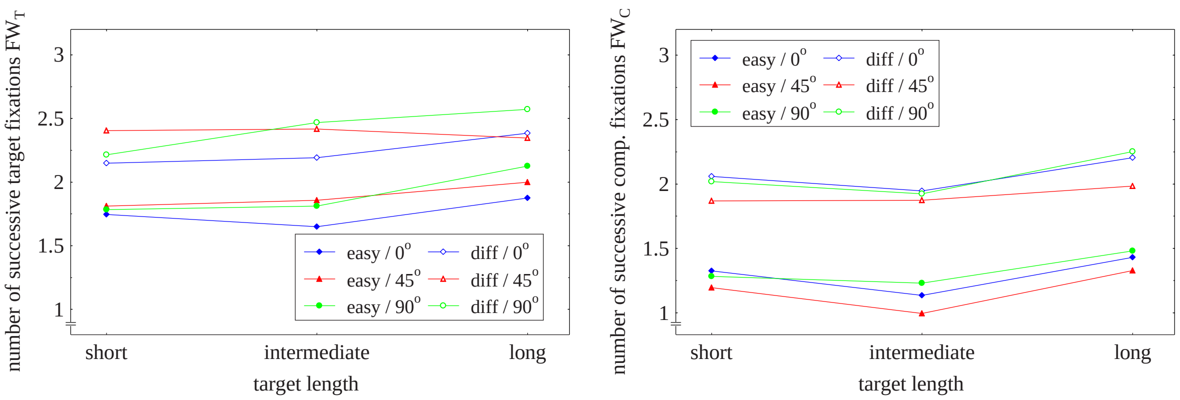


Figure 11.13: Average number of successive fixations within the target hemifield FW_T (left) and within the comparison hemifield (right) as functions of target line segment length, separated for the three target orientations and the discrimination difficulty.

investigated before we can check for possible differences between the number of successive fixations within each of the two hemifields. The analysis of variance yields the same significant main effects for all factors on FW_C as it did for FW_T before. Thus, the influence of the discrimination difficulty constitutes a highly significant effect on FW_C $(F(1;33) = 163.01; p < 0.001)$ with the area in proximity to the comparison stimulus being successively fixated 1.27 times before directing the eye gaze to the target hemifield in the easy discrimination condition. FW_C increases to 2.01 when the length similarity is high, i.e. the discrimination difficulty. The factor target line segment length also yields a significant main effect on FW_C $(F(2;66) = 13.39; p < 0.001)$. When the target length is short, the mean FW_C is computed to 1.62 successive fixations, when intermediate to 1.52 and when long to 1.78 fixations. Separated for the two discrimination levels, FW_C is 1.27, 1.12 and 1.41 for short, intermediate and long targets when the line segments have a low length similarity and 1.98, 1.91 and 2.15 when the length similarity is high. Finally, the target line segment orientation exerts a significant main effect on FW_C as well $(F(2;66) = 10.54; p < 0.001)$. With FW_C being almost identical when the target is oriented either horizontally (1.68) or vertically (1.69), it does not come as a surprise that the Newman-Keuls test only classifies the differences between these two orientation levels and the oblique level – where FW_C is 1.54 – as statistically significant and being responsible for the significance of the main effect. The test yields $(R_{crit} = 0.072; p < 0.001)$ for the difference between the orientation factor levels horizontal and oblique, $(R_{crit} = 0.074; p = 0.699)$ for the difference between horizontal and vertical and $(R_{crit} = 0.084; p = 0.001)$ for the difference between oblique and vertical. Separated for the two discrimination levels, FW_C is 1.30, 1.17 and 1.33 for horizontal, oblique and vertical targets when the line segments have a low length similarity and 2.07, 1.91 and 2.06 when the length similarity is high. The two- and three-way interactions between the factors do not reach significance level. Figure 11.13 (right) visualises the means for the number of successive fixations within the comparison hemifield FW_C for the three target orientations and the discrimination difficulty as a function of target line segment length.

The subsequent direct comparison of the numbers of successive fixations within the target and the comparison hemifields yields a significant main effect for the factor "hemifield" ($F(1;33) = 17.62; p < 0.001$). Whereas, on average, 2.10 successive fixations occur in the target hemifield (FW_T) before a shift to the other hemifield, FW_C measures only 1.64 successive fixations. As computed in the separate analyses already, the individual means for FW_T and FW_C compare 1.85 to 1.27 in the case of an easy discrimination and 2.35 to 2.01 in the difficult length discrimination condition. Figure 11.14 illustrates the relevant means for the comparison of FW_T and FW_C for the two discrimination difficulties, for clarity reasons in two separate graphs either as a function of target line segment length (left) or orientation (right).

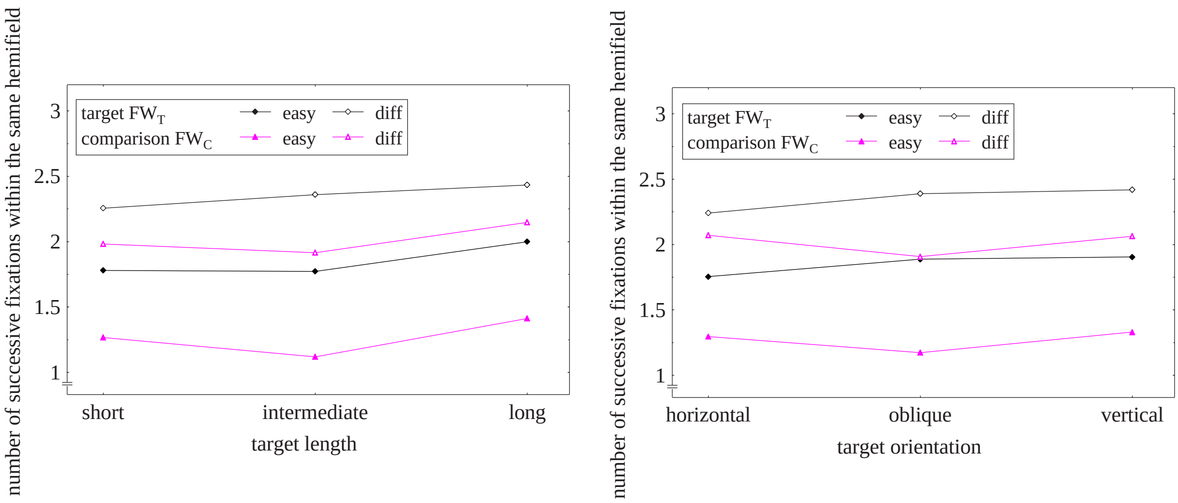


Figure 11.14: Comparison of the number of successive fixations within the target (FW_T) and the comparison hemifields (FW_C) for the easy and difficult discrimination conditions as a function of target line segment length (left) and orientation (right).

Saccade Length SL

In addition, a achieve a more global understanding of the comparison process, the saccade length between the two relevant stimulus regions SL_b will be investigated again in this experiment. Due to the very small number of fixations within the intermittent stimulus section, the saccade length will also be computed "locally" for those saccades that occur entirely either within the target (SL_T) or the comparison hemifield (SL_C) of the display only.

An analysis of variance tests the effects of the factors discrimination difficulty, target line segment length and orientation on the saccade length between the two hemifields SL_b. It yields significant main effects for all factors on SL_b: ($F(1;33) = 1.79; p < 0.001$) for the discrimination difficulty, ($F(2;66) = 17.18; p < 0.001$) for target length and ($F(2;66) = 2.74; p < 0.001$) for target orientation. When the two stimulus line segments have a low length similarity, the average SL_b is computed to 19.08^o and when the length similarity is high to 19.79^o. The comparison of means further shows that SL_b decreases from 20.96^o for short target line segments, through 19.65^o for intermediate to

17.65^o for long line segments. When the target line segment is oriented horizontally, SL_b covers 18.93^o, 19.36^o for oblique and 20.01^o for vertical targets. When SL_b is separated for the two discrimination conditions, the analysis of variance also reveals that saccades between the two stimulus hemifields are significantly longer for all target lengths when the discrimination is difficult (21.23^o for short, 19.90^o for intermediate and 18.21^o for long targets) than when it is easy (20.69^o, 19.41^o and 17.10^o). In addition to the observed main effects, the interaction between the two factors target line segment length and orientation also reaches significance ($F(4; 132) = 1.33; p < 0.001$). This can be attributed to the observation that, when horizontal target line segments are presented, SL_b decreases more rapidly from short through intermediate to long targets than when oriented obliquely or vertically. No other interactions reach significance level. Figure 11.15 charts the mean values of SL_b as a function of target line segment length, separated for the three target orientations and the two discrimination difficulties.

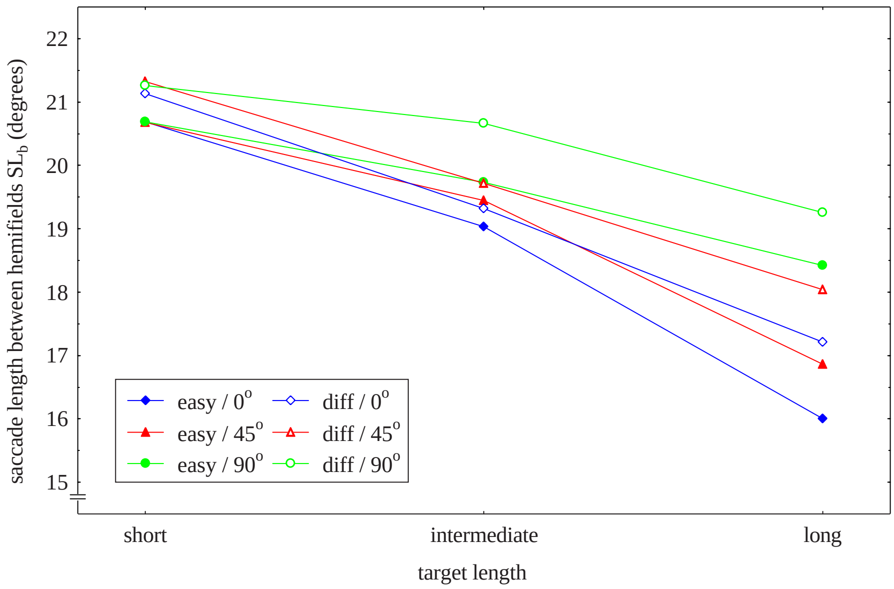


Figure 11.15: Saccade length between the two stimulus hemifields SL_b as a function of target line segment length and orientation, charted for the two discrimination difficulties.

We will now consider the "local" saccade lengths, namely SL_T and SL_C, for saccades whose start and end points are both located within either the target or the comparison hemifield. The analysis of variance for SL_T shows a significant main effect of the factor discrimination difficulty thereupon ($F(1; 33) = 1.50; p < 0.001$). When the line segments display low length similarity, the mean SL_T is 3.23^o, but decreases to only 2.37^o for high length similarity. The effect of the factor target line segment length on SL_T also reaches significance ($F(2; 66) = 4.66; p < 0.001$), the saccade lengths measure 1.19^o for short target line segments (1^o), 2.88^o for intermediate (6^o) and 4.53^o for long line segments (11^o). Separated for the two discrimination conditions, the mean SL_T is computed to 1.26^o, 3.42^o and 5.31^o for the three target lengths when the discrimination is easy. When the two line segments are difficult to discriminate, SL_T is 1.13^o, 2.32^o and 3.90^o for short, intermediate and long targets, respectively. This notably steeper increase in SL_T with target lengths for the easy than for the difficult discrimination condition is also manifested in a significant interaction between these two factors ($F(2;66) = 0.38; p = 0.002$).

The third factor, target line segment orientation, exerts a significant effect on SL_T as well ($F(2;66) = 0.69; p < 0.001$), the saccade lengths measure 3.23^o for horizontal target line segments, 2.73^o for oblique and 2.54^o for vertical segments. Separated for the two discrimination conditions, the mean SL_T is computed to 3.64^o, 3.22^o and 2.85^o for the three target orientations when the discrimination is easy. When the two line segments are difficult to discriminate, SL_T is 2.83^o, 2.23^o and 2.06^o for horizontal, oblique and vertical targets, respectively. Whereas this interaction does not reach significance level ($F(2;66) = 0.01; p = 0.807$), the interaction between target line segment length and orientation does ($F(2;66) = 0.21; p = 0.008$). This can be attributed to SL_T means that more sharply increase over target length when oriented horizontally – 1.21^o (short), 3.32^o (intermediate) and 5.16^o (long) – than obliquely – 1.18^o, 2.90^o and 4.10^o – or vertically – 1.18^o, 2.41^o and 3.76^o. None of the remaining two-way or the three-way interactions exert significant effects on SL_T. Figure 11.16 (left) charts the means for the saccade lengths within the target hemifield SL_T for the three target orientations and the discrimination difficulty as a function of target line segment length.

In contrast to SL_T, the analysis for the saccade lengths within the comparison stimulus hemifield SL_C shows significant main effects for the factors discrimination difficulty ($F(1;33) = 2.54; p < 0.001$) and target line segment length only ($F(2;66) = 14.01; p < 0.001$). For the easy discrimination condition, SL_C on average measures 4.17^o, for the difficult one 3.21^o. The comparison of means further yields that SL_C increases from 1.24^o for short through 3.69^o for intermediate to 6.12^o for long target line segments. As for SL_T, SL_C shows a steeper increase over target length when the discrimination is easy than when it is difficult. Means for this interaction significantly vary ($F(2;66) = 0.78; p < 0.001$) and yield 1.28^o, 4.27^o and 6.92^o for short, intermediate and long target line segments when the

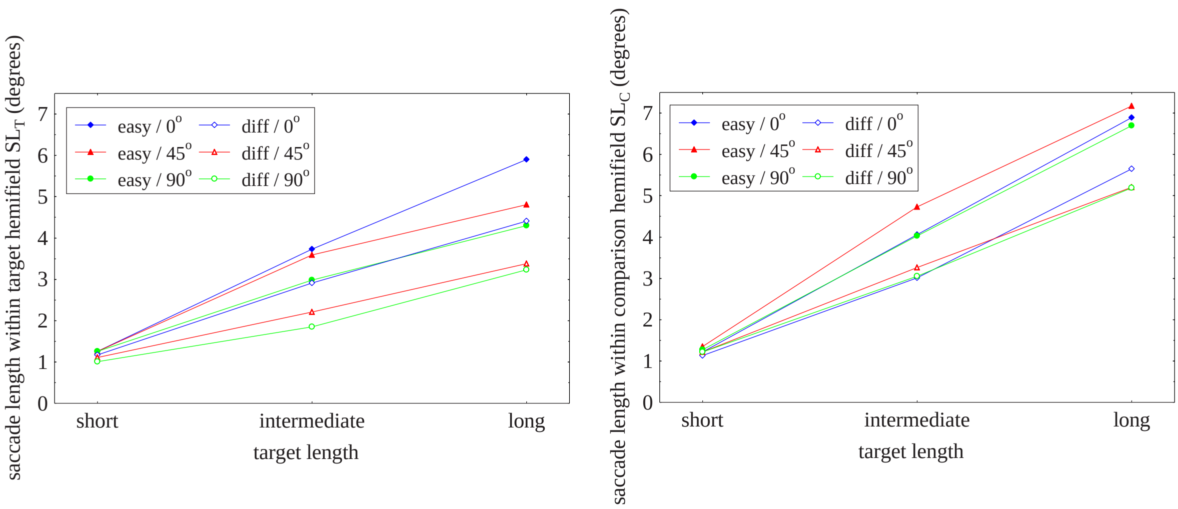


Figure 11.16: Saccade length within the target hemifield SL_T (left) and within the comparison hemifield SL_C (right) as functions of target line segment length and orientation, charted for the two discrimination difficulties.

discrimination is easy and 1.19^o, 3.11^o and 5.32^o for the target length levels in the case of a difficult discrimination condition. Here, no significant effect on SL_C can be established for the factor target line segment orientation ($F(2;66) = 0.13; p = 0.114$). Irrespective of the target orientation, SL_C measures approximately 3.63^o. The other two- and three-way interactions do not reach significance level. Figure 11.16 (right) charts the means for the saccade lengths within the comparison hemifield SL_C for the three target orientations and the discrimination difficulty as a function of target line segment length.

Again, we directly compare the saccade lengths within the target (SL_T) and the comparison hemifields (SL_C). The statistical analysis yields a significant main effect for the factor "hemifield" ($F(1;33) = 2.59; p < 0.001$). Whereas the average saccade length in the target hemifield is 2.80^o, it measures 3.69^o in the comparison hemifield. As computed in the separate analyses already, the individual means for SL_T and SL_C compare 3.24^o to 4.17^o, respectively, in the case of an easy discrimination and 2.37^o to 3.22^o in the case of a difficult length discrimination condition. Figure 11.17 illustrates the relevant means for the comparison of SL_T and SL_C for the two discrimination difficulties, for reasons of clarity in two separate graphs either as a function of target line segment length (left) or orientation (right).

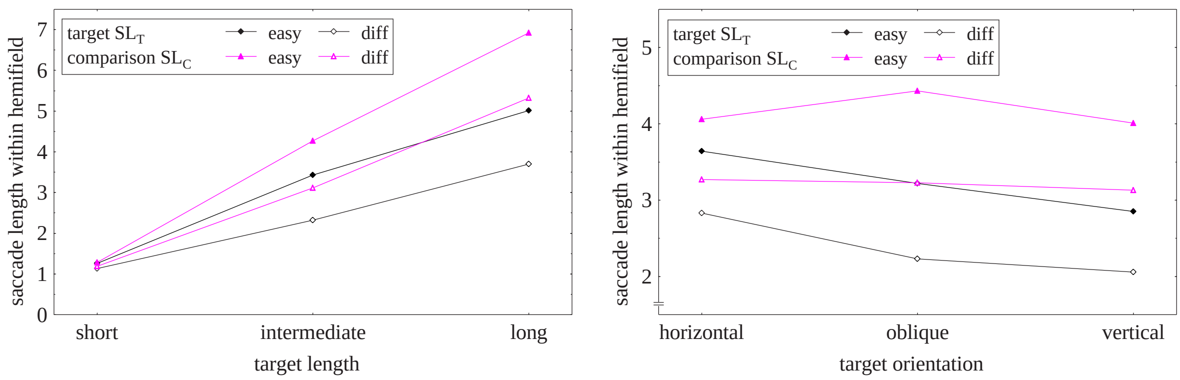


Figure 11.17: Comparison of the saccade lengths within the target (SL_T) and the comparison hemifields (SL_C) for the easy and difficult discrimination conditions as a function of target line segment length (left) and orientation (right).

11.4 Discussion and Conclusions

The discussion of the results of the previous Experiment S1 has demonstrated that the perception principles that determine the simultaneous comparison of line segment length prove a lot more complicated as could initially have been expected. The empirical findings yield that even "simple" line segment stimuli and the assessment of their basic features such as length trigger diverse, characteristic visual analysis patterns guided by elaborate cognitive strategies. For the then applied "dynamic" length matching procedure the discussion revealed *foveal "visual measurement"* as a fundamental mechanism to accomplish the (line segment length) assessment "step" of the characteristic cognitive structure of comparison tasks (see Section 2.1). For longer line segment lengths, this strategy was adapted to a *"fractional"* visual measurement and the subsequent length extrapolation in order to improve efficiency, assumedly *decomposing* the line segment and taking into account peripherally perceived end point information. Accordingly, mental line segment *representations* were generated, memorised and manipulated.

However, the dynamic adjustment procedure apparently influenced some observations in Experiment S1, for example regarding the fixation durations FD which were prolonged in the comparison hemifield (for details, see Section 10.3). This rendered the procedure at least critical when assigning specific observations – as intended – solely to the actual line segment assessment task. The current static method of constant stimuli should now have helped in eliminating these undesirable "side effects". As the lengths of the comparison line segments were set in accordance with the *perceived* target lengths of Experiment S1, possible interference of visual illusory effects can also be excluded. The experimental findings of Experiment S2 should be less ambiguous and allow for further reliable conclusions regarding the underlying principles of line segment length perception. The findings will be discussed with particular respect to the initially hypothesised different strategies that subjects apply depending on the discrimination difficulty: *Holistic* or *analytic* visual processing when the length discrimination task is *"easy"* or *"difficult"*, respectively.

The following are the most outstanding effects the factors in Experiment S2, namely the discrimination difficulty, target line segment length and orientation, exerted on the independent variables, i.e. the discrimination correctness, the reaction time and the various eye-movement parameters:

1. As expected, the discrimination correctness DC reaches almost 100% when the discrimination task is "easy". The "difficult" discrimination condition indeed appears to be difficult as less than two thirds of all responses are correct.

2. Both "conventional" variables such as the reaction time RT and eye-movement parameters such as the number of fixations NF, the number of fixations within the same hemifield FW or the number of saccades between hemifields SB are significantly higher when the discrimination is difficult. These findings are compatible with the view that a holistic visual processing strategy is pursued when the line length similarity is low and an analytic one when it is high.

3. More generally speaking, the factor discrimination difficulty exerts a significant effect on all dependent variables but FD_I.

4. The factor target line segment length exerts a significant effect on all dependent variables.

5. The factor target line segment orientation exerts significant effects on most dependent variables: DC, NF, NF_I, FD_I, SB, FW, FW_T, FW_C, SL_b and SL_T. However, fixation duration, the "local" numbers of fixations NF_T and NF_C, the reaction time

RT and the saccade length within the comparison hemifield SL_C are not significantly affected.

On the one hand, the statistical analysis of the discrimination correctness DC serves as a *"control"* function. Almost 100% of all subjects' responses are correct when the length differences between the target and the comparison line segments are set so as to establish "easy" discrimination conditions. This confirms the findings of the pre-experiment and demonstrates that length discrimination is indeed *easy* when the similarity of line segment lengths is *low*. The fact that DC is considerably lower when the length differences between the target and the comparison line segments are set so as to establish "difficult" discrimination conditions not only proves that length discrimination is indeed *difficult* when the similarity of line segment lengths is *high*. It also shows that the two discrimination conditions are sensibly chosen to yield significant differences between them. This indicates that such differences might exist between the two conditions with respect to the other dependent variables as well. This is highly promising with a view to the anticipated different visual processing strategies.

Furthermore, it is important to note that subjects' responses in the difficult discrimination task are well *above chance level*. The difficult condition is apparently not too difficult. If it was, subjects would make random decisions. This would probably coincide with sparse visual scanning because a more detailed visual analysis might not be rendered helpful in such a case – yielding an unwanted "random" rather than the intended "difficult" discrimination condition.

However, DC is not just a convenient "control" variable that successfully demonstrates that the two discrimination conditions were sensibly established. The significant differences in DC between the different target length and orientation levels when the discrimination is difficult require further discussion. Initially, it appears contradictory to the previous findings, for example, that DC is *best for short line segments*. The previous experiments yielded the least accurate results when subjects had to assess length or orientation of short line segments, both in sequential or simultaneous comparison scenarios. A closer look reveals, however, that exactly this might have caused the good discrimination performance here. Let us recall that the relative length deviation DL between the target and the comparison line segments was largest when subjects had to assess short targets and adjust the comparison accordingly in Experiment S1. As we used these length deviations – and associated standard deviations – to determine comparison lengths in Experiment S2, (relative) length differences between target and comparison line segments will consequently be largest for short targets here. As results of this experiment now demonstrate, this obviously facilitates the binary discrimination task to such an extent that it leads to the highest discrimination correctness DC for short line segments. It thus appears that line segments that are short are the most difficult ones to assess and match – i.e. the assessment accuracy is worst compared to other lengths – in the dynamic length adjustment task of Experiment S1. Given the less demanding binary comparison task of Experiment S2, length differences of a magnitude not detected and compensated for by adjustment in Experiment S1 are now correctly identified. The dynamic assessment task obviously interferes with the length perception processes insofar as it also compromises the assessment accuracy.

In analogy to making the binary discrimination task in Experiment S2 easier for short length – due to larger length deviations DL in Experiment S1 – a similar development could have been expected for the orientation levels. With DL being significantly larger when targets and comparisons were not equally oriented, the discrimination could have been thought to be easier and yield a higher discrimination correctness DC for oblique and vertical target orientations. This, however, is not the case. It must be assumed that the length differences in the difficult discrimination condition only compensate for the horizontal-vertical illusion induced by the different orientations of the target and comparison line segments. Other than obviously the case for short target length, the larger length differences for oblique and vertical orientations do not facilitate the comparison and thus do not affect the discrimination correctness DC. Even when the comparison length is set so as to compensate for the illusory effects, it is obviously a lot more difficult to compare lengths when the respective line segments are not equally oriented.

The analysis of the reaction time in Experiment S2 fits in well with the discussion of RT in the previous experiments. Compared with Experiment S1 which had an average RT of approximately 4620 ms, average reaction times of approximately 910 ms in the easy and approximately 2000 ms in the difficult discrimination condition appropriately reflect the *less demanding* method. Only the binary decision of which of the two line segments is longer is required. The time-consuming process of dynamically matching the length as in Experiment S1 does not have to be accomplished anymore. Subjects now compare the static representation of the length of one stimulus constituent with the memorised and recalled representation of the other. Subjects might actually save extra time not only because of the procedure itself, but also – although closely related to it – because no dynamic adaptation of the mental representation of the comparison stimulus after adaptation steps is necessary.

The reaction times for the two discrimination conditions are more than just a slight hint towards very different assessment strategies pursued by subjects, depending on the similarity of line segment lengths. Although they provide little insight into the processes that govern each strategy – exactly how subjects perceive the scene – it must be assumed that the *short* RT in the *easy* condition does not allow enough time for a thorough *foveal* analysis. Cognitively challenging principles as “visual measurement” and extrapolation mechanisms will probably not be feasible; efficient peripheral processing might rather have to be applied. In contrast, the *extended* RT when the lengths of the target and comparison line segments are *similar* should give enough time to apply just these proposed visual processing mechanisms. We can thus expect to find support for either *holistic* or *analytic* visual processing strategies. In addition, taking the discrimination correctness DC into account, we also see that even analytic, quite complex visual strategies and cognitive processing are not able to compensate for the higher task complexity. When the discrimination task is “easy”, coarse, holistic visual processing still yields significantly better results.

The significant increase of RT from short to intermediate and long target line segments was also noted in Experiment S1. In Experiment S1, we could only speculate about the possible causes. After the subsequent discussion of the eye-movement data in Experiment S1, it becomes clear that the increase of RT in Experiment S2 might again be a consequence of an increase of the number of fixations that are necessary to assess longer line segments – assuming that similar visual perception strategies/principles such as visual measurement apply in Experiment S2 as well. In analogy, the generation, memorisation, recall, comparison and matching – however not the adaptation as in the dynamic Experiment S1 – of the corresponding mental representation becomes an increasingly complex cognitive task. For longer line segments, more *"constituents"* have to be integrated into the representation. The fact that significant differences in RT only exist between short and intermediate and short and long line segments, but not between intermediate and long ones, indicates, however, that maybe only a distinction between short and "longer" has to be made. A step-by-step, multi-fixation analysis of each line segment might not be required. *Two-fixation measuring* could be sufficient, even for long line segments. This appears to be likely when we further consider that – at least in Experiment S1 – only fractions of the line segments were visually scanned.

The lack of a significant effect of the target orientation on the reaction time might explain why the discrimination correctness DC decreases for oblique and vertical targets – compared to targets that are horizontally oriented. We can thus conclude that comparisons of *not co-linearly oriented* line segments are indeed *more* complicated. When we further consider that this is so although the comparison length is being compensated for the illusory effects, the previous assumption that "basic" orientation differences between two stimuli alone complicate the comparison appears even more likely. Subjects do not seem to be aware of the higher complexity, otherwise they could have been expected to compensate for it, for example by a more thorough visual analysis. This would certainly have resulted in increased reaction times for unequally oriented line segments. However, that is not the case in Experiment S2.

Again, it appears that the discussion of *eye-movement data* will be indispensable for understanding the underlying visual processing and perception principles that are characteristic for the assessment and simultaneous comparison of the lengths of line segments. Undisturbed by a dynamic adaptation process as in Experiment S1, the discussion here should provide even more insight into the visual strategies of "pure" length perception. The particular focus here lies on the differences between the hypothesised *holistic* and *analytic* assessment strategies. As the discussion of DC and RT strongly suggests that these might indeed exist, the discussion of the eye-movement parameters should provide "evidence" for or against them. In particular with respect to the analytic variant, we can expect to obtain clear information on how foveal information is integrated into a model that yields the representation of line segment lengths and how this representation is manipulated and matched with other (length) representations.

As in Experiment S1, the distinction between *global* and *local* eye-movement measures appears appropriate. In particular for the difficult discrimination task we can assume a strategy that combines distinct global and local processes which have to be accounted for accordingly. To prove that the assumed locations of designated "areas of interest" for the investigation of local parameters were sensibly chosen, another cluster analysis (k-means clustering with $k = 2$) was computed. The clustering and a subsequently applied principal component analysis yielded similar results to that of the corresponding procedures in Experiment S1. Reflecting the obvious observation that fixation points are again cumulated in proximity to the target and comparison line segments, two ellipses (marked red in Figures 11.5 and 11.6 for the easy and difficult discrimination conditions, respectively) approximate the fixation distribution.

In principle, the characteristic ellipses features shape, location and orientation lead to the same implications as in Experiment S1: The offset of the center of gravity of the ellipses suggests that target line segments are *only partially assessed foveally* and that their lengths are extrapolated, possibly taking into account peripheral visual information. The direction of the offset towards the display center for horizontal targets and towards the upper end point for oblique and vertical ones also speak for an efficient visual strategy that *takes into account the part of the target line segment only that is closer to the comparison* – as far as foveal assessment is concerned. The shapes of the ellipses support that indeed only *parts* of the target line segment are considered, in particular when the targets are longer.

Not unexpectedly, the *orientations of both the target and the comparison ellipses again resemble that of the respective line segments*. Furthermore, in contrast to the observations in Experiment S1, both the comparison and the target ellipses very accurately do so when the discrimination task is difficult. Even for oblique and vertical orientations, the target ellipses are correspondingly oriented. It can thus be assumed that fixations indeed quite accurately follow the line segments during the local scanning, possibly again *"visually measuring"* the line segment lengths – a strong indicator for an *analytic* strategy that might be applied when the lengths of the comparison and target line segments are similar and thus difficult to discriminate. On the other hand, even when the discrimination is easy the principal axes of the ellipses show a *strong co-linearity* to the respective line segments. This indicates that even then some analytic visual processing rather than pure holistic perception might be applied. Probably the fact alone that double as many intermittent fixations occur when the discrimination is easy than when it is difficult will cause the ellipses to tilt less – and thus not as closely resemble the target orientation as it does in the difficult discrimination condition.

Figure 11.18 shows two characteristic gaze trajectories in this experiment. The upper one was recorded during the assessment of two line segments whose lengths were easy to discriminate, the lower one when the discrimination was difficult. These trajectories qualitatively illustrate the differences between the two visual processing strategies. Furthermore, they convincingly reflect the distributions of fixations and also offer qualitative support for the holistic and analytic natures of the strategies.

Having established a "safe ground", proving the validity of the chosen measures via the computational methods of clustering and PCA in this experiment as well, the discussion of the specific eye-movement parameters will now attempt to clarify the existing uncertainties regarding the pursued visual strategies.

The more *global* measures will be addressed first. In order to test the hypothesis that two rather different visual processing strategies are pursued to solve the simultaneous

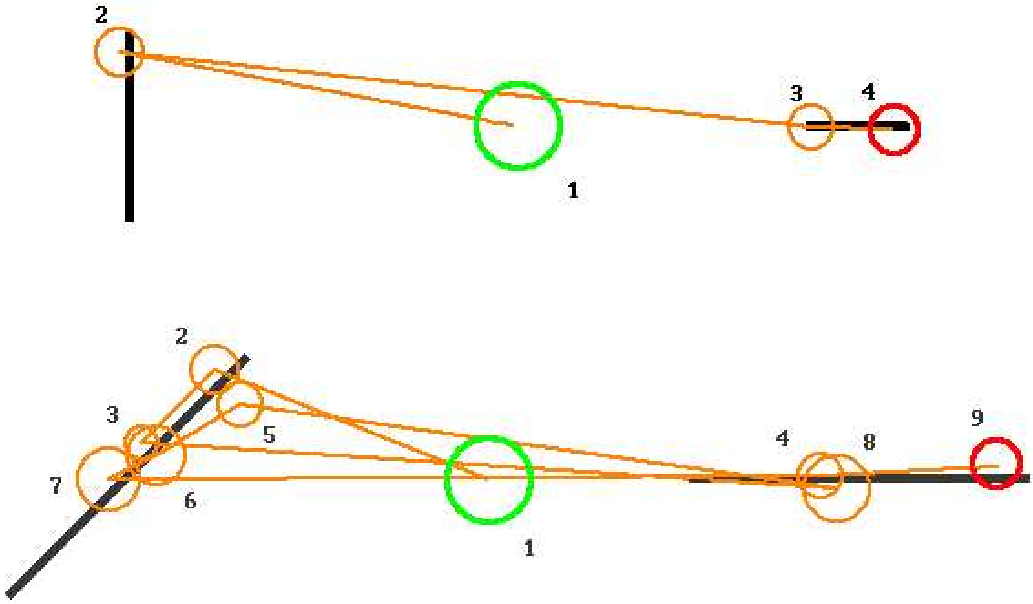


Figure 11.18: Typical gaze trajectories in the easy (top) and difficult (bottom) discrimination conditions, reflecting the holistic and analytic visual processing strategies, respectively. Numbers show the temporal sequence of fixations; circle size signifies fixation duration.

length discrimination task, the global and local numbers of fixations NF, NF_T, NF_C and NF_I and of the number of saccades between hemifields SB provide the most promising basis for discussion. Although FW and SL are certainly better suited for the subsequent discussion of the local processes of these strategies, NF, NF_T, NF_C, NF_I and SB should still provide valuable, at least initial insight in this respect as well.

For a start, the overall number of fixations NF clearly indicates a more thorough visual analysis of the scene when the discrimination is difficult. More than double as many fixations occur than in the easy discrimination condition. Comparing the local NFs with the overall numbers of fixations demonstrates that subjects almost exclusively fixate in either the target or the comparison stimulus areas. Only between 2% (difficult discrimination) and 4% (easy discrimination) of all fixations lie in the intermittent display section. Taking the distributions of the fixation locations into account as well, it can be very confidently stated that *line segments are indeed foveally viewed during the comparison task and that very little global peripheral visual processing takes place.* This is certainly not surprising for the difficult length discrimination task which was supposed to be analytic.

With respect to the easy discrimination, however, we could at first not be sure on which *level* holistic perception would occur. The observations of the number of fixations, the fixation location distributions and the number of inter-stimulus saccades start to clarify this point now. It can be concluded that probably no *global holistic* visual processing strategies are applied. Although twice as many intermittent fixations occur when the discrimination is easy, the low percentage – remembering that only 4% of all fixations are intermittent ones – rules out that subjects assess and compare the two stimuli peripherally in such a way that they fixate a position at the display center. It appears more likely that a *local holistic* visual processing of the target and comparison line segments takes place. In general, subjects only fixate once in proximity to each stimulus constituent, but do rarely analyse the respective line segments by multiple successive fixations in the easy discrimination condition – as we expect to find when the discrimination is difficult. However, even the easy discrimination could require such analytic visual scanning in some cases.

The closer inspection of the absolute number of saccades between the stimulus hemifields shows that it is sufficient to generate a reliable representation of a line segment and its length by only looking *once* at a each line segment in the easy discrimination condition. Attention is paid to one of the line segments, its internal representation is generated and memorised. Based on the findings of the eccentricity Experiments E0–E2 it can be assumed that the line segment is *decomposed*. The length representation is obtained by *fusing* the peripherally perceived location data of the end points. Then, attention typically shifts to the other line segment, the previous length representation is recalled and compared with that of the currently fixated line segment. In some cases, attention shifts back to the other line segment, probably for validation purposes.

When the lengths of the two line segments are similar, subjects require significantly more shifts of attention, coinciding with the *repeated update* of the mental representations. Each line segment is viewed between two and three times before subjects arrive at a conclusion which of the two is longer. Due to the higher task complexity, such an analytic visual processing strategy is applied. Consequently, much more foveally acquired information has to be integrated into the representations. This makes generation, memorisation and recall for matching a lot more complicated so that multiple shifts of attention are necessary to obtain reliable representations. The analysis of DC demonstrated however, that, in terms of correctness, these representations cannot really be considered accurate or "reliable".

Target length and orientation influence the global eye-movement measures as well. In general, they do so in a similar manner as in Experiment S1 so that analogous conclusions can be drawn here. The overall number of fixations significantly rises when the length of targets increases, indicating that the *assessment of longer lengths is a considerably more complex task*. To meet these higher cognitive demands that longer line segments pose for an appropriate generation and manipulation of the corresponding representations, more foveal information has to be integrated. This is particularly so when the discrimination is difficult and an analytic visual scanning strategy is pursued. Such an increase can also be found in the local numbers of fixations. Both NF_T and NF_C rise for longer line segments, again particularly so when the discrimination is difficult. In contrast to the previous Experiment S1, NF_T is not significantly different from NF_C any more. This supports the assumption that the dynamic adjustment procedure in Experiment S1 was indeed at least partially responsible for the significantly higher values of NF_C, compared to those for NF_T. The method of adjustment apparently complicated the assessment of the comparison line segment whereas now the method of constant stimuli successfully eliminates such effects. The observations in Experiment S2 can thus be more reliably attributed to the actual length perception processes alone.

The interpretation of the orientation effect on the number of fixations – or the lack thereof – is slightly more complicated than in Experiment S1. First, discovering that the overall number of fixations NF is affected by orientation presents a surprise when we consider that neither NF_T nor NF_C significantly vary between the three target orientations. This only leaves NF_I, which was found to significantly increase when the target and comparison stimuli were not co-linearly oriented, to account for the significant orientation effect on the overall number of fixations. This, however, is not intuitively explicable as NF_I only accounts for a very small fraction of the overall number of fixations.

Discussed in isolation, the lack of a significant orientation effect on either NF_T or NF_C suggests that probably similar visual processing strategies – at least on the global level – are pursued in both display hemifields irrespective of the orientation. Although it is not clear whether a more thorough foveal analysis would have helped to improve the assessment accuracy in the difficult discrimination condition for longer line segments, the subjects' significantly poorer performance (see analysis of the discrimination correctness DC) certainly renders the pursued strategy inadequate in that respect. Subjects should at least have attempted to compensate for the obviously higher complexity of a comparison of two line segments that are not equally oriented. A corresponding conclusion was drawn from the findings in Experiment S1 already. There, the reluctance to adapt the number of fixations was assumed to contribute to the stronger effects of the horizontal-vertical illusion on the length adjustment error.

Although we already noted that the very low absolute number of intermittent fixations NF_I renders the interpretation of this measure problematic (also see Section 10.3), it still allowed for the conclusion that global peripheral perception processes are obviously negligible for this binary simultaneous length comparison task – not also only when line segment lengths are similar, but also when they are largely different and thus easy to discriminate. Furthermore, the close correspondence between the findings of Experiments S1 and S2 with respect to NF_I, FD_I and the angle between a saccade to and the subsequent one from an intermittent fixation point supports the previous *"landmark" assumption.* Fixations in the intermediate display section serve as "landmark" orientation points which are only being *passed "on the way"* from one line segment to the other. In Experiment S2, the fixation duration in the intermittent section FD_I is significantly shorter than those in the two stimulus sections, and, probably even more important, considerably shorter than the reaction times measured in the Experiments E0–E2. In particular the reaction times measured in the eccentricity experiments can be assumed to yield reference FDs that enable accurate peripheral processing of line segments in order to assess their lengths. Thus, FD_I as measured in Experiment S2 is probably too short to allow for explicit peripheral perception.

The angle between two successive saccades that pass through the intermittent display section supports the assumption that this section is indeed only "passed": Now, in 92% of all cases the angle is larger than 135% – irrespective of the discrimination difficulty. Under the "landmark" hypothesis, the significant decrease of NF_I from short through intermediate to long target lengths and the significant increase of NF_I from horizontal through oblique to vertical target orientations can be understood: Following the argumentation of

Experiment S1, long(er), in particular horizontal line segments are more closely located to each other than short ones so that intermittent fixations are not required to guide the gaze from one stimulus constituent to the other. In addition, when the gaze moves over from the horizontal comparison stimulus to an oblique or vertical target, or, more specifically, to its upper part (see results of the PCA, Figures 11.5 and 11.6), often an intermittent fixation might be required to change direction from the horizontal to an upwardly directed saccade. In analogy to the discussion of Experiment S1, this process could also contribute to significantly higher numbers of fixations in the intermittent display section for oblique or vertical targets. However, it must be remembered that no reference could be found in literature that reports a similar pattern of the inter-stimulus gaze trajectory.

Apart from SB, the saccade length between the two stimulus hemifields SL_b must be considered for discussion in the context of global shifts of attention. As the factors target line segment length and orientation produce almost identical effects on SL_b and as the statistical analysis yields rather similar means as in Experiment S1, analogous conclusions can be drawn here (also see Section 10.3). In short, the principal findings thus indicate that the gaze is indeed guided by the stimuli and suggest – globally – a predominant foveal processing rather than a global peripheral perception strategy. Even when the discrimination task is easy the two line segments are apparently at least once foveally viewed. Furthermore, the fact that SL_b is again shorter than the distance between the two line segments' center points suggests that the *innermost* parts of a line segment are evaluated, pointing to a "lean" visual processing strategy. This is also supported by the discussion of the distribution of fixations and the corresponding principal component analysis.

In contrast, the discussion of the overall fixation duration FD and of the local FD_T and FD_C here must lead to rather different conclusions than those drawn from the findings in Experiment S1. Not too surprisingly, however, longer FDs in the difficult discrimination condition could be expected. Subjects obviously render it a successful visual strategy to execute more fixations that also last longer in an attempt to compensate for the higher task complexity. The longer fixation durations can be considered clear indicators for more complex perceptive and cognitive processes that are accomplished during fixations when line segments with high length similarity are compared. Let us assume the analytic processes here can be characterised by similar mechanisms as for the length assessment in Experiment S1. First, the very accurately, foveally "visually measured" length of the line segment has to be acquired and computed at each fixation point. In addition, the (size of the) fraction of the line segment has to be obtained with equal accuracy, probably by peripheral visual processing. This information must then be integrated into the current representation of the line segment at each fixation point. It is thus quite understandable that the generation and update of such a mental representation of line segment length takes considerably longer – manifested in longer fixation durations – than in case of an easy discrimination task. The coarse line segment representation then requires less intense, "holistic" visual processing and can be generated more quickly – coinciding with shorter fixation durations.

Other than during dynamic length matching, the fixation durations increase for longer line segments in Experiment S2. Looking back at the findings in Experiment S1 reveals, however, that the decreasing overall fixation FD from short (339 ms) through intermediate (309 ms) to long target lengths (285 ms) had to be entirely attributed to a corresponding such effect in FD_C (494 ms, 374 ms and 322 ms for the three target lengths, respectively). For FD_T, the effect of the factor target length on the target fixation duration reversed, FD_T was approximately 220 ms when short targets were presented and rose to about 245 ms for intermediate and long ones. The increase of FD, FD_T and also that of FD_C in the current Experiment S2 does consequently not come as a surprise any more. Not being directly affected by the dynamic adjustment procedure in Experiment S1, FD_T already suggested this increase when "stable" objects have to be perceived – which is confirmed here for both the target *and* the comparison fixation durations in Experiment S2. This yields further evidence that the dynamic adjustment procedure itself significantly influences visual perception as already discussed in detail in Section 10.3.

Finding a significant interaction effect between the discrimination difficulty and the target length on all FD, FD_T and FD_C further complicates the discussion. This requires two different explanatory approaches that can account for the increase of these fixation times for longer line segments, depending on the discrimination difficulty. So, why do fixation durations constantly increase with target length when the target and comparison line segments have low length similarity whereas FDs significantly differ only for short line segments (compared to intermediate and long ones) when length similarity is high?

Let us consider the latter – high similarity – case first. Here, it appears that for short line segments only, the generation and manipulation of a corresponding mental representation requires less cognitive processing at each fixation point. Still assuming "visual measurement" and peripheral fraction extrapolation as the key mechanisms for the analytic visual processing mode, only the visual measurement component is required for the generation of a mental representation of short line segments. This is supported by the findings regarding FW and SL in Experiment S1, only then line segments are obviously *entirely* visually measured. Thus, less information has to be cognitively processed and integrated into the line segment representation at each fixation. For both intermediate and long line segments the additional (peripherally) perceived "fractional" information has to be integrated, thus prolonging the fixation times.

In contrast, an (assumedly) holistic processing strategy is applied when the length similarity is low. With this strategy, which conceivably very much depends on (local) peripheral rather than on foveal processing, the peripheral perception of line segment lengths certainly becomes more difficult the further away from the fixation point the relevant information is located – as is the case for the end points of longer line segments. To compensate for this obviously increasing complexity of the task with increasing line segment length, subjects extend fixation duration correspondingly. This is supported by the findings in the eccentricity Experiments E0–E2 that yielded an increase in the reaction times – which can be considered corresponding measures to the FDs measured in the current Experiment S2 – when stimuli were presented at even more eccentric locations.

So far, we established that obviously two distinct visual processing strategies exist and how these strategies differ on a more *global* level when subjects have to solve either an easy or a difficult length discrimination task. What remains now is the discussion of the local eye-movement measures in order to explore whether the hints for *local* holistic and analytic processing, found in the global measures already, are indeed confirmed. Undisturbed by adjustment procedures, we should then have created a rather comprehensive "image" of the visual perception processes and their interaction that determine the underlying strategies during line segment length assessment. The following paragraphs will show if such local visual scanning strategies are actually pursued: Mainly *peripheral* processing when the discrimination task is easy, and *foveal "visual measurement"* of specific line segment' fractions paired with *peripheral extrapolation* when the discrimination task is difficult.

First, the overall number of successive fixations within the same hemifield FW and its local derivatives FW_T and FW_C strongly support these assumptions. The large differences between the values of these measures in either the easy or the difficult length discrimination task clearly indicate that rather different visual strategies are pursued on the local processing level as well. Finding that significantly more successive fixations occur within each hemifield for the difficult discrimination yields further support for one of the principal hypotheses, namely that the visual strategy can be described as "analytic". In contrast, the few successive fixations that occur when the target and the comparison lengths are easy to discriminate may intuitively justify classifying the corresponding visual strategy as "holistic". However, what really renders the strategies analytic and holistic and reveals their specific "nature" are the absolute values of the FWs rather than the relative differences between them for the two discrimination conditions.

Let us consider the processing strategy in case of an easy discrimination first. In fact, the values of FW as measured during the easy discrimination task can hardly be considered "successive" at all. Only about 1.5 successive fixations occur within each hemifield, i.e., on average, only every second shift of attention between hemifields is followed by two successive fixations in the same hemifield. In the remaining fifty percent of the cases, only a single fixation occurs before attention is shifted between stimuli constituents again. This certainly does not allow for an analytic scanning of the respective line segment and the visual measurement of its length. The discussion of the local numbers of fixations further reveals that significantly more successive fixations occur in proximity to the target line segment than in proximity to the comparison one. With FW_C being only 1.2 on average, it becomes clear that the comparison in particular is only fixated once before attention shifts back to the target hemifield. This very sparse fixation "pattern" that shows a single fixation in the comparison hemifield in 80% of all cases only allows for the peripheral perception of the comparison length. According to the initial "definition", this certainly constitutes a holistic visual processing strategy.

On the other hand, the average FW_T of 1.8 indicates that the target line segment is not entirely holistically perceived although the discrimination is (supposed to be) easy. In a considerable number of "visits" to the target stimulus, two successive fixations are executed, possibly to visually measure its length. This is the case in particular when line segments are longer, thus even in the easy discrimination task apparently not all relevant length information can be reliably perceived peripherally. An average FW_T of 2.0 clearly indicates a rather analytic process for this specific situation. Furthermore, when targets are “long”, the visual strategy becomes more analytical in the comparison hemifield as well. Finally, finding FW_T significantly higher than FW_C can be understood when we consider the orientation effects. Is is apparently more difficult to assess targets that are not co-linearly oriented to the respective comparison, a foveal analysis of the oblique and vertical target is required. Although such target orientations influence FW_C also, it mainly results in an increase of FW_T, yielding the overall higher numbers of successive fixations within the target hemifield.

In summary, the *discussion of the number of successive fixations within the same hemifield in case of an easy discrimination task yields strong support for a largely holistic visual processing strategy.* Sparse fixation patterns *often only show a single fixation* rather than a more detailed visual analysis of the line segment before attention shifts to the other display hemifield. This clearly indicates that the perception of line segment length in easy discrimination tasks is mainly a *peripheral* visual process. However, given certain obviously complex target–comparison combinations of long and not co-linearly oriented line segments, a tendency to foveally analyse the target stimulus becomes considerably more pronounced. In those cases, probably a quite accurate target representation obtained through (partial) foveal length measurement is compared with a coarse comparison representation, generated by local peripheral processing when fixating a (central) point on that line segment. As the target line segment can be oriented obliquely and vertically – whereas the comparison is always presented in a horizontal orientation – its visual perception in general can be rendered more complex and obviously requires a higher number of successive fixations than for the comparison. However, FWs in the easy discrimination condition certainly do not imply a thorough analytic visual perception strategy.

This is the case when the discrimination is difficult. The number of successive fixations within each hemifield suggests a more detailed foveal visual scanning of both stimulus constituents and yields a strategy which we can classify as entirely “analytic”. All FWs *strongly support the specific assumption that about two fixations occur that could be required to visually measure the length of a line segment or parts thereof when the discrimination is difficult.* As FW varies between approximately 2.1 for short targets and 2.3 for long ones, this strategy appears to be feasible even for such line segments that could completely be assessed foveally. Unlike in Experiment S1, where FW suggested that short line segments only sometimes required more than just one fixation in order to assess their length, here FW indicates that this is always so. Due to the task difficulty, subjects obviously find it advisable to fixate even short line segments about twice. Presuming that the visual measurement principle holds, only the exact foveal end point processing probably allows them to reliably determine the line segment length by computing the distance of its end points. Although we have not discussed the implications of the saccade lengths yet, the distribution of fixations already implies that the successive fixations are indeed positioned so as to enable visual measurement. Taking into account that these fixations are again located on or at least in close proximity to the respective line segment is a further indication in favour of such a visual strategy.

Although it now appears that this specific analytic processing strategy is pursued irrespective of the length of the line segments, significant difference still exist. The average FW clearly in excess of two when targets are long(er) shows that in a considerable number of cases three successive fixations must occur. The comparison of FW_T and FW_C further yields that this is even more so for fixations that are located in proximity to the target line segment. As in the easy discrimination condition, the target is the apparently more complex one to assess and thus demands a more detailed foveal analysis.

A number of explanations exists to motivate the third successive fixation in these cases. It would, for example, be possible that the FWs increase during the assessment of longer line segments because subjects sometimes have to execute a *corrective* saccade after shifting attention from one display hemifield to the other. However, this could rather have been expected when short line segments were shown. The distance between the two line segments is then larger than in case that long line segments have to be assessed. Accordingly, longer inter-hemifield saccades are required for short line segments. The longer the saccades become, the more prone they generally are to inaccurate "landings" with respect to the intended destination. This might then require a corrective saccade, however, in the given scenario for short line segments rather than for long(er) ones.

Instead, it is more likely that the visual measurement directly causes the third successive fixation. It could either be that the third fixation "lands" back on where the first one was located. The same distance would be measured once again, i.e. the two corresponding saccades *alternate* "back and forth" over the line segment or a designated fraction of it. This could be done in order to *enforce* or to *improve* the mental representation. Alternatively, a *"step-by-step"* multi-fixation analysis could be thought of that successively integrates smaller line segments and their visually measured lengths into the overall line segment representation. An analysis of the angles between successive saccades does not yield support for only one of these two alternatives. When at least three successive fixations occur in either hemifield, in about 30% of these cases an angle below 20^o suggests "alternating" saccades. In about 60%, an angle between 160^o and 200^o apparently speaks in favour of the "step-by-step" visual scanning.

Although the target orientation exerts significant effects on all FWs, the number of successive fixations within the target hemifield FW_T exhibits a more prominent such effect than FW_C. As the target line segment is shown in different orientations, but not the comparison one, it appears that only such direct influence (of orientation) manifests in corresponding effects. When the target and the comparison line segments are *not co-linearly oriented, subjects obviously try to compensate for the higher comparison complexity by a more thorough local visual analysis of the target stimulus.* On average, every second "visit" to the target hemifield constitutes three successive fixations rather than just (the overall average) two. This cannot be found when the comparison line segment is analysed which is always oriented horizontally. Subjects obviously do not transfer the higher orientation-induced complexity of co-linearly oriented line segments to the comparison hemifield in such an "indirect" way that the number of successive fixations within that hemifield FW_C also increases when the target is obliquely or vertically oriented. This certainly considerably contributes to FW_T being significantly higher than FW_C. In general, we can assume that this difference is thus due to a more detailed local visual analysis of the target line segment. This is apparently required in order to account for the higher complexity of the perception and following cognition processes of not co-linearly oriented line segments in the difficult discrimination task. The generation and matching of representations must be expected to be particularly complicated by intermediate mental manipulation mechanisms. Here, the *mental rotation* of one line segment must be accomplished (e.g. see Johnson-Laird, 1983) to facilitate the comparison of line segments (and their representations) that are not co-linearly oriented.

This now only leaves the discussion of the *visual measurement hypothesis*. The analyses of the saccade lengths within the two stimulus hemifields SL_T and SL_C again provide the reliable basis to validate the assumption that this indeed is the fundamental local processing principle of line segment length assessment, in particular when the target and comparison line segments demonstrate high length similarity. However, as the statistical analyses of these saccade lengths could only take saccades into account that were entirely located within a hemifield, at least two successive fixations within that hemifield are required. In that case, we assumed earlier that even for the easy discrimination condition subjects conduct a detailed foveal analysis of a line segment, probably visually measuring its length. We might thus not expect to find similarly large differences in the respective saccade lengths between the two discrimination conditions as for the previously investigated eye-movement parameters.

In general, the saccade length data yields great support for the conclusion that visual measurement is in fact the principal underlying mechanism of visual length perception and assessment – at least for difficult discrimination tasks in the given simultaneous comparison scenario. Finding that the *saccade lengths within both the comparison and the target hemifields very closely resemble the lengths of the respective line segments when these are short* indicates a very “pure” such principle for this length level. The entire length is visually measured, not just a certain fraction of it. The respective number of successive fixations of almost exactly two when line segments are short and difficult to discriminate (see previous paragraphs) further confirms that this only requires a single saccade. No successive, step-by-step multi-fixation scanning strategy is pursued. Finally, the distribution of fixations demonstrates that indeed the respective line segments are fixated rather than any other locations within the comparison or target hemifield.

The detailed analysis of the values of SL_T and SL_C for short line segments inspires further discussion. Assuming that such (short) line segments are indeed visually measured as described above, saccade lengths actually exceed the line segment lengths. Interestingly, this is even more so in the target hemifield than in the comparison one. On first sight, this appears contradictory to the results of the statistical analysis which demonstrates that SL_T is shorter than SL_C. However, we must take into account that Experiment S1 revealed an overestimation of the lengths of target line segments. In order to create line segments that are perceived as equally long, the physical length of comparisons had to be increased in Experiment S2 accordingly. Not surprisingly, the statistical analysis now yields absolute SL_Cs that are longer than the absolute SL_Ts. Nevertheless, the comparison between the physical target length and SL_T showed greater differences than that between the physical comparison length – which is not equal to the perceived comparison length –

and SL_C. Apparently, the comparison line segments are more accurately visually measured than the target ones. However, the absolute differences are rather small.

Furthermore, the correlation between the saccade lengths and the discrimination difficulty is higher when the target and comparison line segment lengths are similar. In that case, subjects obviously try to very accurately visually measure both the target and the comparison lengths in an attempt to facilitate the difficult discrimination task. When subjects apply this more detailed visual analysis in an easy discrimination task – which only happens occasionally as the previous discussion of NF and FW demonstrated – this is apparently done less "accurately", probably influenced by the holistic processing strategy they generally pursue in such cases. Orientation aspects seem to play no important role here, short target line segments are visually measured equally accurately as the respective comparisons, even when the two line segments are not co-linearly oriented. However, the higher correlation between saccade SL and line segment length in the comparison hemifield persists.

In contrast to the "pure" visual measurement strategy that subjects pursue when line segments are short, the perceptive and cognitive processes that characterise the length assessment become more complicated for longer lines segments. As in Experiment S1, SLs suggest that only *fractions* of line segments are visually scanned. It appears likely that this partial length data must be integrated into an according mental representation along with additional information on the entire line segment length. Due to the lack of further saccades and the fixation distributions/PCAs which only imply "visits" to one – and, when repeated, to the same – part of a line segment, the "fraction size" can obviously only peripherally be acquired. Although significant differences exist between SL_T and SL_C, it can be assumed that this *"fractional visual measurement"* strategy is pursued in both hemifields to solve the discrimination task. Taking the FWs into account also, it becomes clear that subjects apply this strategy mainly when the line segment lengths are similar.

In analogy to Experiment S1, the analytic visual strategy for such a difficult length discrimination task thus appears to comprise the following processing steps: A certain section of one of the two line segments is visually measured and the length of the "measuring saccade" is internally represented and memorised. In addition, a "multiplication" factor must be stored to represent the ratio between the viewed fraction and the overall line segment length. As discussed in detail in Experiment S1, this factor representation is generated implicitly, i.e. an abstract numerical representation is stored rather than an imagery line segment representation made up of the viewed line segment fraction and the multiplication factor. As very little foveal scanning of the outermost half of the line segments can be observed, it is likely that the essential information for the storage of the fraction data is acquired peripherally and might again require the *decomposition* of the line segment as lined out earlier. The fraction data might thus be represented in terms of the distance between the peripherally perceived outermost end point and one of the fixation points that contribute to the actual measuring saccade of the respective line segment. Attention then shifts to the other line segment where the same procedure is repeated to assess an equally sized fraction of that line segment and mentally represent its length as well. Next, the previously stored length representation is recalled and the memorised representation of the line segment fraction and the multiplication factor are compared to those of the currently viewed line segment. If this comparison does not produce a considerable difference – which can easily be the case when the discrimination is difficult and differences are accordingly small – attention shifts back and the comparison procedure is re-iterated, employing updated representations, until the "mental matching" produces a notable length difference between the target and comparison length representations.

Finally, the specific saccade lengths yield insight into the *value* of the multiplication factor. Intuitively, it can be speculated that possibly *half* of the line segment is visually measured, yielding an "easy" to represent multiplication factor of value two. In fact, the current experimental setting seems to further encourage this, in particular when the target is either obliquely or vertically oriented. As clearly visible, for example in Figure 11.1, the comparison line segment, when moved over to the left, would intersect the target one in the middle. If we imagine that the subjects' gaze follows the horizontal orientation of the comparison line segment when attention shifts to the target hemifield, it might easily meet the target just there and yield a convenient first fixation point for the subsequent visual (target) measurement.

Indeed, the saccade lengths seem to yield considerable support for just such a sectioning, in particular when we also consider the number of successive fixations within each hemifield. Within the target hemifield, SL_T accounts for between 35 and 40% of the target line segment length when it has intermediate or long length, respectively. When we further take into account that for such lengths often more than just two successive fixations occur in the target hemifield (30–40% of all "visits" to that hemifield show three successive fixations) this combination of SL_T and FW_T yields an average total visual measurement length within that hemifield – before attentions shift to the comparison – that covers about 50% of the target line segment length. However, as the discrimination correctness drops considerably the longer line segments are, it apparently becomes increasingly more difficult to maintain, manipulate and correctly recall the mental representations that involve more complex generation steps. Often, three-step-fixations make up the visually measured length and the accurate peripheral end point perception becomes more difficult also because longer line segments require processing in further peripheral areas.

When the target orientation is not co-linear to that of the comparison line segment, SL_T drops significantly, but FW_C does not increase accordingly for compensation. This could be the possible reason for a worse discrimination correctness DC when targets are obliquely or vertically oriented, compared to horizontal ones: Subjects still assume they visually measure and represent half the target stimulus, but they actually do not. Alternatively, the shorter visually measured line segment could mean more peripheral processing which must also be achieved in further peripheral regions. According to the findings of the eccentricity Experiments E0–E2, this might render the length assessment in the current scenario less accurate as well. As, at the same time, SL_C is not influenced by orientation this certainly leads to more false discrimination decisions. Finally considering SL_C in conjunction with FW_C further confirms the representation of halves of line segments: SL_C almost exactly coincides with 50% (48% for intermediate, 47% for long length) of the (physical) comparison lengths while FW_C measures very accurately two – as already mentioned, both variables irrespective of target orientation. Thus only a single saccade is executed within the comparison hemifield that approximately visually measures half its lengths.

11.4.1 Summary

The fundamental conclusion that can be drawn from the current Experiment S2 is that two very distinct visual processing strategies can be established, depending on the discrimination difficulty. Furthermore, the discussion convincingly demonstrates that these strategies can indeed be classified as either *"holistic"* or *"analytic"*. In accordance with the initial "definition" of holistic, subjects only *coarsely visually scan* line segments that exhibit a low length similarity. When length similarity is high which makes the discrimination difficult, a *detailed foveal analysis* of the line segments is conducted to accurately assess and represent their lengths for a subsequent mental comparison.

More specifically, the two strategies significantly differ on two levels that are characteristic for the simultaneous comparison scenario employed here. Reflected by corresponding eye-movement parameters, a rather different visual "behaviour" is found to describe the inter-stimulus, *global* processing strategy. In analogy, characteristic differences also exist on the *local* level, describing the intra-stimulus processing.

When the discrimination task is easy, the experiments yield strong support for a holistic processing strategy. A closer look reveals that this strategy is *locally* holistic rather than *globally*. Initially, the latter variant was hypothesised, assuming that subjects fixate a center position on the display and try to globally peripherally perceive lengths of the target and comparison line segments. Data shows, however, that subjects even in the easy discrimination condition usually fixate each stimulus constituent (at least) once. They locally peripherally assess the length of the respective line segment. A single fixation is found to be sufficient in almost all cases to successfully accomplish the discrimination task. As the further findings strongly indicate that the end points of the line segments are of particular relevance for length assessment, this very sparse fixation pattern only allows for a coarse perception of the line segment lengths and constitutes a process that is certainly entirely peripheral.

In some cases, subjects do not exhibit this local holistic behaviour even when the discrimination is classified "easy". A more analytic strategy is pursued instead and two successive fixations within the same hemifield are executed. This only occurs in the target hemifield where the orientation can change between horizontal, oblique and vertical. When the target and the (always horizontally oriented) comparison line segment do not have a co-linear orientation, a detailed foveal analysis of the target is obviously helpful. This is in particular so when the assessment is further complicated because the line segments are long and cannot be that easily perceived peripherally. In this case, the analytic visual perception process is thought to yield a more accurate target length representation, mentally rotated to match the comparison orientation, and subsequently compared to the comparison representation. The comparison length is perceived peripherally so that this process must still be classified as "locally holistic".

In all cases, the generated representations are accurate enough to instantly correctly discriminate the lengths. Only a single shift of attention between the two stimulus constituents is sufficient before subjects make their decision. In summary, the easy length assessment and discrimination task can reliably be classified as a "locally holistic" process. The pursued visual strategy almost entirely relies on the peripheral processing of the relevant line segment information. This then yields sufficiently accurate mental representations of line segment lengths in order to ensure a reliable length comparison and discrimination.

When the discrimination task is difficult, the sketched analytic visual processing strategy is pursued throughout. The empirical data supports *local, foveal "visual measurement"* as a fundamental principle to assess line segment lengths within both the target and the comparison hemifield. This visual measurement principle is generally characterised by two successive fixations within the same hemifield. Even more than in the previous Experiment S1, these fixations are located "on" the target or the comparison stimulus. The saccade length between the two fixations closely coincides with the overall length of the respective line segment when it is short or, when longer, only covers a specific, rather innermost, fraction of the line segment. In particular the generation of mental representations of obviously complex target line segments – such as those that are long and not co-linearly oriented to the comparison – often requires step-by-step visual analysis of the target where three successive fixations are executed. In a considerable number of these cases, gaze also alternates between two designated locations on the line segment and can be thought to "enforce" the length representation or to improve the representation accuracy.

Additional information on the size of the fraction in relation to the overall length is also stored along with the mental representation of the saccade length(s) for the subsequent comparison. This is probably achieved by incorporating peripherally perceived information on the outermost end point of the line segment in question. Data indicates that apparently half of the overall physical length of the respective line segment is visually measured, constituting a "multiplication" factor of *two*. When data perceived by multiple successive fixations must be integrated, the addition of several saccade lengths obviously demands greater cognitive and memory "effort" in order to store, maintain and compare the various representations. Such representations, which are made up of data that is increasingly complex to integrate, are apparently not ideal. The discrimination correctness considerably decreases in such cases.

In analogy to the findings in Experiment S1, eye movements further indicate that after the visual measurement of one of the two stimulus constituents and the generation of a corresponding mental representation, attention directly shifts to the other line segment. No or only little peripheral information is taken into account during the global phase of the comparison process. The comparison stimulus is analogously assessed, i.e. visually measured, and the correspondingly generated representation mentally compared with the previously memorised one. If the two representations are not found to yield a significant difference in perceived length, the comparison procedure is repeated and the mental comparison is executed again with the updated representation. In contrast to the easy discrimination condition, these global shifts of attention and the subsequent procedure are re-iterated several times when the discrimination is difficult in order to increase the accuracy of the representations – until the length discrimination task can be solved.

Length assessment apparently requires the *decomposition* of the line segments both in holistic and analytic mode. The assessment of the locations of the line segment end points is of particular relevance. For local peripheral processing that is characteristic in holistic mode, length is mentally represented and memorised as the distance between one end point that is foveally viewed and the second end point that is peripherally perceived. For the foveal visual measurement of length in analytic mode line segments must be decomposed so that their end points provide landmarks for the measuring saccades.

In summary, the discussion should then have created a rather comprehensive image of the visual perception processes and their interactions that determine the underlying strategies during line segment length assessment. In particular the analysis of eye-movement parameters proved essential in this respect. Undisturbed by dynamic adjustment procedures, we could proceed to assigning specific observations solely to the actual line segment assessment task. This finally yields *support for the hypothesised holistic and analytic strategies* that subjects pursued and and helps understanding the underlying visual processing and perception principles that are characteristic for the assessment and simultaneous comparison of the lengths of line segments. Furthermore, we could gain insight into the generation and manipulation of corresponding mental line segment representations.

The following chapter now attempts to implement a comprehensive computational model, integrating components of the previous “eccentricity model”, that successfully mimics the visual length assessment strategies as applied by subjects in the simultaneous comparison tasks of the Experiments S1 and S2.

Chapter 12

Modelling Similarity Effects

Let us recall the sequence of procedural steps while exploring eccentricity effects on the visual perception of various stimulus dimensions such as location, length and orientation. Following the data acquisition and the proposal of possible interpretations of the observations (Experiments E0–E2, see Chapters 5, 6 and 7), a computational model could successfully be implemented in Chapter 8. In general, this approach achieved a good reproduction of the empirical data. The model demonstrated a particularly convincing performance in this respect with regard to the peripheral assessment of the length of line segments that were presented in a sequential visual comparison scenario. Many characteristic effects of peripheral orientation perception were also adequately accounted for by the implementation. Being based on the decomposition hypothesis, the model thus presented support for the proposed perception mechanisms that apparently characterise the different steps of the cognitive structure of comparison tasks, namely assessment, memorisation and comparison. We can now hope to obtain similar benefits from the development of an extended model to simulate the effects of *similarity* on the perception of line segments (lengths).

12.1 A Model for Simultaneous Length Assessment/Discrimination

Ideally, a computational model should be able to reproduce the empirical findings as recorded in the Experiments S1 and S2. We will thus attempt to advance a formalised description of the procedure subjects pursue when they accomplish a simultaneous length comparison/discrimination task. The challenge will be to parameterise this process so that an algorithmic implementation reproduces the empirical data while taking into account the hypothesised perception mechanisms. This then allows us to directly compare the empirical and simulated data sets in order to validate the correctness of the model. In case of a positive correlation, we will not only have developed a working model, but also obtained considerable support for the correctness of the assumed underlying perceptual mechanisms that govern human length assessment .

The following sections motivate the model idea, determine the modelling preliminaries and explain the methods in detail. The implementation of the model is described and finally the results of the simulation are presented and discussed with respect to the empirical findings of the Experiments S1 and S2.

12.2 Model Motivation, Concept and Structure

The underlying ideas for the modelling approach pursued here were briefly introduced in the previous chapters. We will now develop these ideas in detail and lay out the procedural structure of the model.

The discussion of the findings of Experiment S1 revealed that subjects were apparently distracted from the "pure" length perception task by the dynamic adjustment procedure. This often made it difficult to assign specific observations solely to the dynamic adjustment process or to the actual line segment assessment task. The static scenario of Experiment S2 eliminated such "side-" effects previously induced by the dynamic adjustment procedure. In an attempt to account for the subjects' visual assessment, memorisation and comparison strategies and reduce the influence of the dynamic adjustment procedure, the current model approach will thus mainly focus on the findings of Experiment S2. The implementation primarily aims at simulating the length assessment and discrimination task of Experiment S2 rather than the adjustment procedure/steps of Experiment S1. However, it will also attempt to replicate the target overestimation effect of Experiment S1, induced by the horizontal-vertical illusion. Let us consider the processing steps in detail.

Experiment S2 has clearly established two distinct visual processing strategies. Depending on the discrimination difficulty, subjects perform either a *holistic* or an *analytic* visual analysis of the scene. The initial distinction between these two "modes" must certainly be accounted for by the model. After switching to one of the modes, the accordingly assigned visual scanning strategies must be represented. These were found to significantly differ on two levels, namely the *global* level, describing the visual inter-stimulus processing, and the *local* one, describing the intra-stimulus processing.

Globally, for example, fewer shifts of attention are characteristic when the discrimination is easy than when it is difficult. This further varies with the other factor combinations. In particular when the target and comparison line segments are long and not co-linearly oriented, the number of inter-stimulus shifts can significantly increase, even when the discrimination task is classified as easy. The global visual scan-pattern then resembles the one that can normally be expected for a difficult discrimination task.

Similar dependences can be observed when considering the local visual processes. In case of an easy discrimination task, only a rough visual scanning of line segments must normally be represented in the model. Isolated, single fixations on the line segments indicate that much information is only peripherally processed rather than foveally. Line segments are certainly not visually measured via saccades. However, the model implementation must account for the fact that a rather detailed foveal analysis may also be pursued in easy discrimination tasks for certain factor combinations of line segment length and orientation. Such a detailed foveal analysis of the line segments on the local processing level is generally required in the analytic model mode, i.e. when the length discrimination is difficult. Let us now consider in greater detail how these characteristic procedural steps for simultaneous line segment length assessment/discrimination can be represented.

12.2.1 Pre-attentive Mode Selection

First, an initial distinction between the two modes – holistic vs. analytic – must be made. Viewing this distinction as a global peripheral length assessment task appears to be a promising idea. It is apparently accomplished *pre-attentively* at the beginning of each trial when subjects fixate at the center of the display, half way between the stimulus constituents. From this fixation point they peripherally assess the length of both the target and the comparison line segments and (mentally) compare their two lengths. Although we learned from the eccentricity Experiments E0–E2 that such peripherally acquired representations only roughly represent the actual (physical) object dimensions, such representations should prove accurate enough to decide whether the two line segments are of similar length or not. Accordingly, either the analytic or the holistic processing mode for the subsequent visual scanning is chosen. However, when the two line segments are not co-linearly oriented, a mental rotation is required for the comparison of their peripherally perceived lengths. This additional mental processing step obviously deteriorates the representation accuracy and makes the discrimination more difficult even when the (physical) length differences are obvious. This is reflected by switching to analytic rather than holistic mode although the discrimination might actually be easy.

It appears realistic that subjects indeed initially ”make up their minds” about which strategy to follow rather than doing so at a later stage of the discriminiation/comparison process: The fixation duration FD (348 ms) of the initial fixation at the display center is significantly longer than the mean FD (231 ms) of those measured subsequently ($F(1; 33) = 21.73; p < 0.001$). This at least strongly suggests that subjects may allow sufficient time for the sketched initial peripheral length assessment of the two stimulus constituents. In the current model, this initial peripheral length assessment will be modelled as the assessment of two positional markers in their specific eccentricity region – the two end points of the target and the comparison line segments – relative to the central fixation point. The subsequent computation of their distances as introduced when modelling eccentricity effects in Chapter 8 then yields the lengths of the target and the comparison line segments. These processing steps thus propose the *decomposition* of line segments and the *fusion* of end points to yield line segment length.

Depending on the difference of these rough, initial length assessments either the analytic (small difference) or the holistic model mode (large difference) will be activated for subsequent processing. As already indicated in the previous paragraph, subjects may not only obtain rough length data from this initial local peripheral assessment of the line segments, but also information regarding their orientation. According to the standard deviations for peripheral length and orientation assessment in Experiments E1 and E2, both length and orientation data should be more than accurate enough to (coarsely) classify lengths as either short, intermediate or long and orientations as either horizontal, oblique or vertical. The classification within the current scenario is even more coarse-grained and should thus be achieved more reliably: Here, the relative orientation of two line segments must only be classified as being co-linear or not. Although the eccentricity model did not produce quite as accurate results for the simulation of the peripheral orientation assessment as it did for the length assessment, it will also be used to yield this classification of lengths and orientations. As these factors were found to significantly influence the subjects' visual strategies, the model should certainly "know" these stimulus attributes in order to adequately account for their impact on the subsequent model processing steps.

Once in either holistic or analytic processing mode, subjects follow the corresponding visual strategies already sketched – in holistic mode a rough, locally peripheral visual processing of line segments with few shifts of attention between stimulus constituents or, in analytic mode, a detailed foveal scanning of line segments to accomplish "visual measurement" of line segment lengths, paired with multiple inter-stimulus saccades. How can these visual scan paths and the respective eye-movement parameters be simulated adequately?

12.2.2 Saccade Planning

The planning and execution of successive saccades presents one of the main goals – or challenges – for the generation of "artificial" gaze trajectories similar to those of subjects. In order to determine the "landing" point of a saccade, i.e. the subsequent fixation point relative to the current one, almost exclusively peripheral information on possible fixation "candidates" is available. In particular with abstract stimuli the planning of saccades is thought to be an almost entirely peripheral process (e.g. Abrams, 1992; Findlay, 1992). No or only little conceptual information is provided to guide attention otherwise. In the current scenario, which is definitely an abstract one, it can thus reliably be assumed that (the location of) the end point of a saccade must be determined peripherally. As the location assessment in Experiment E0 demonstrates, this again can only be achieved with a specific location accuracy/uncertainty. In order to realise saccade planning and execution, the model approach chosen here should integrate the findings of the eccentricity Experiments E0 and E1 and the modelling principles of eccentricity effects. The saccade's landing point should therefore be modelled in analogy to the model introduced in Chapter 8 as a peripheral location assessment. However, another question remains which must be answered before any saccade can be executed: How can the point be determined that yields the "landmark" for the saccade landing?

Simple line segments obviously only provide very few "locations of interest". The (statistical) investigations of saccade lengths and the (qualitative) visualisations of gaze trajectories suggest that only the end points of line segments (and probably mid points as well) "qualify" in this respect. Data further suggests that preferably those end points closest to the current fixation are considered likely candidates, in particular for inter-hemifield saccades. This then mainly determines the global aspects of how to realise the shifts of attention between the two stimulus hemifields/constituents. In principle, the subsequent saccades within each hemifield can be modelled analogously. However, depending on the processing mode, the empirical fixation patterns vary significantly. The model has to take this into account as well.

12.2.3 Holistic Mode

Local Peripheral Assessment

When the discrimination task is initially classified as being easy, often only one fixation at the landing point of the inter-stimulus saccade occurs and no saccade is executed within the (same) hemifield. In this case, the second end point of a line segment is peripherally assessed from the currently fixated end point. It is not fixated for foveal assessment and no saccadic visual measurement takes place. The distance between the peripherally assessed location and the current fixation point then yields the length of the line segment. This distance must be mentally mapped and memorised for the subsequent comparison with the length of the other line segment: After (overtly) shifting attention to its hemifield, i.e. a saccade to one of the end points – usually the innermost one – of the other line segment, the method of local peripheral length assessment as just described is reapplied. This generates a corresponding representation of the length of the second line segment. In most cases of easy discrimination tasks the subsequent comparison of the memorised length representation with the newly generated one yields sufficiently discrepant lengths – although it must further be assumed that the accuracy of the memorised representation decays over time. The model will then terminate and yield a response without further shifts of attention or iteration of the local assessment processes.

Analytic Processing in Holistic Mode

However, such an extremely sparse fixation pattern cannot always be observed when solving an easy discrimination task. The modelling should thus also allow for the somewhat more analytical, detailed foveal processing patterns, which can be observed in some cases. Here, the described local peripheral length assessment is applied to only one of the stimulus constituents, usually the comparison line segment. In contrast, the target line segment is assessed analytically: After shifting attention from the comparison hemifield to the target one by a saccade "landing" in proximity to the innermost end point of the target line segment, a second fixation will subsequently be executed "on" that line segment. For short line segments, i.e. those with "foveal" length (see definitions in Sections 3.2.2 and 9.1), a saccade to the other end point is planned and accordingly executed. This saccade planning and execution will be represented in the model as the peripheral location perception of the outermost line segment end point, viewed from the first fixation point on the line segment. The saccade will then be executed towards the location which is computed using the method introduced for modelling eccentricity effects in Chapter 8. For short line segments the resulting landing point of that saccade is determined within the accuracy that location estimation yielded for the eccentricity region I in Experiment E0 (see Chapter 5). According to the assumption of "visual measurement" of line segment length, the length of the saccade will be mentally represented as the length of the respective line segment.

More interestingly, the saccade planning for intermediate and long line segments, i.e. those with “parafoveal” and “peripheral” lengths (see above), demonstrates an even more complex cognitive structure – proposed in Sections 10.3 and 11.4 and now to be adequately represented in the model. Again, the planning of the saccade within one of the hemifields takes into account the distance between the line segment’s two end points. However, as the empirical data revealed that often only one half of the line segment is visually measured, the modelling procedure differs in some respect. As previously explained for short line segments, the location of the outermost line segment end point is peripherally assessed from the first fixation point on that line segment. The distance is computed accordingly (see above) to judge the length of the line segment. Unlike before, this (mental) overall length representation is apparently (mentally) intersected in the middle to yield the representation of half the line segment. Now, the intersecting point rather than the outermost end point of the line segment serves as the landing point of the saccade.

This additional processing step certainly compromises the assessment accuracy and thus the accuracy of the length representation for the subsequent comparison. The comparison, at least for the easy discrimination task which is currently being discussed, is mostly accomplished locally peripherally and does not involve the visual measurement of the respective other line segment. Due to the mental representation and memorisation of half a line segment, this local peripheral assessment must also represent half the line segment only. Such patterns for easy discrimination tasks will mostly be found when the target and the comparison line segments are not co-linearly oriented and/or when the lengths of the line segments are intermediate or – even more so – long.

12.2.4 Analytic Mode

The previous paragraphs outlined how the model should account for the more detailed foveal scanning of line segments under certain conditions when the discrimination is easy. The analytic processing mode in difficult discrimination tasks leads to such visual behaviour throughout – further enhanced by some exceptions which render this procedure even more difficult to simulate.

Foveal Visual Measurement

Normally, the saccade planning and execution will be determined by the visual measurement mechanisms of *both* stimulus constituents. Depending on the line segment lengths, saccades covering either their whole length (short line segments) or approximately half their lengths (intermediate and long line segments) will be executed. The saccade lengths are then mentally mapped and memorised to represent the line segment lengths or specific fractions thereof. These representations are then compared in an attempt to solve the given discrimination task. In principle, the model representation for the saccade guidance will thus be the same as already described. It is again based on modelling the peripheral location assessment accuracy as when modelling eccentricity effects in Chapter 8.

However, in some cases the foveal scanning of line segments to yield (mental) representations of their lengths obviously cannot be achieved by only two successive fixations on the same stimulus constituent before attention (overtly) shifts to the respective other line segment. In such cases the model must also account for the extended visual scanning strategies observed in the empirical data of the Experiments S1 and S2. Accordingly, at least two derivatives of the visual measurement strategy must be represented in the model. These are applied in particular when a difficult discrimination task is further complicated by showing long line segments which are not co-linearly oriented. For such configurations, the second end point of a line segment can only (far) peripherally be assessed from the currently fixated one. Furthermore, a mental rotation of one line segment (representation) might be required to accomplish the comparison.

Extended Foveal Visual Measurement

As one option to solve this complex discrimination task, subjects sometimes execute "alternating" saccades between one end point and the mid-point of a line segment. They probably attempt to amend the representation accuracy of the length by more accurately determining the mid-point and thus improving the visual measurement of the line segment fraction (see Sections 10.3 and 11.4). The model could adequately represent this amendment mechanism when we take into account that from the second fixation on a line segment, namely that one in proximity to the mid-point, both end points are far less peripherally located and can thus be assessed more accurately. The model could then compute the distance between the currently fixated mid-point and either of the two end points. If the difference between these two distances is considered "too large", the visual measurement of the respective line segment fraction must be repeated and attempts to compensate for the intersection error noticed. The newly determined mid-point should now more accurately coincide with the real physical mid-point of the line segment.

Alternatively, the visual measurement is made up not only of two but three successive fixations "in-line" to represent (a specific fraction of) the line segment length. The procedural steps to be modelled here would then be as follows: Again, the location of the second end point of a line segment is peripherally assessed from the other end point. However, rather than visually measuring half of the resulting distance with a single saccade, an intermittent saccade whose length measures about one forth of the entire length of the line segment is executed first. From its landing point the already peripherally assessed location of the one end point can probably be more accurately reassessed because it now appears in a less peripheral region. This amended location and the length information derived therefrom, however, will be more difficult to integrate into a corresponding mental representation for memorisation and comparison. First, the two peripherally assessed distances have to be integrated to yield the fixation points: The first of these distances measures one forth of the entire line segment length. The second, even more complicatedly, should ideally measure one third of the "new" distance between the landing point of the first measuring saccade and the peripherally perceived end point location. This would yield the desired landing point of the second measuring saccade which again lies in proximity to the (physical) mid-point of the line segment. Furthermore, the two visually measured lengths have to be integrated to yield the mental length representation. Finally, as such successive in-line measuring saccades are often only executed within one hemifield, namely the target one, the comparison with the more "conventional" two-fixation measurement might pose another difficulty and further compromise the assessment accuracy.

The general lack of corrective saccades – only very few are executed aiming to improve the assessment accuracy by determining accurate starting and landing points of measuring saccades – shows that usually no further corrective information must be integrated into the length representations. Subjects probably find that the additional integration effort does not contribute sufficiently to the gain in assessment accuracy – or they assume that the higher complexity of the integration step causes the overall representation to deteriorate rather than helping to improve it.

12.2.5 Global Shifts of Attention

Finally, let us consider again the global processing level in difficult discrimination tasks. It is usually characterised by multiple shifts of attention between the stimulus hemifields and according repetitions of the assessment and the actual (mental) matching/comparison processes. Saccades between the two stimulus constituents be initiated when the local assessment of a line segment is complete. If only one line segment has been locally assessed and its length being represented yet, an inter-stimulus saccade will always occur. The respective saccade should land on the end point of the line segment in the other display half closest to the current fixation. This position of the landing point will again be modelled using the mechanisms that can be assumed to guide peripheral location assessment. Intermittent fixations as found in some cases of the empirical data will be modelled as well. Viewed from such an intermittent fixation point (usually close to the display center) the landing point on the innermost end point of a line segment can be determined more accurately – as viewed less peripherally than from within the other display hemifield. If no intermittent fixation "on the way" occurs, one of the few corrective saccades may be executed on "arrival" at the other stimulus constituent. However, this is only the case if the distance between the landing point of the saccade and the actual end point of the line segment (that the saccade aimed at) is "too large".

Inter-stimulus saccades will occur until the discrimination, i.e. the mental comparison of the currently perceived length and the memorised length of the other line segment, yields a sufficiently large difference. This then allows subjects to classify one of the two line segments as the longer one. We hereby assume that repeated visits to the same stimulus constituent amend the accuracy of the already existing representation. The peripheral visual perception of end points and length computation by visual measurement is repeated on subsequent visits to the line segment and can be used to update the existing representation and thus improve its accuracy. The modelling approach will attempt to account for this improvement by a reduced deviation of the peripherally perceived end point location from the actual (physical) one – compared to the last visit. Eventually, after a certain number of shifts of attention the increasingly more accurate length representations should allow for a good discrimination performance. However, the algorithm must not be allowed to re-iterate too often. On the one hand, this would not adequately reflect the empirical

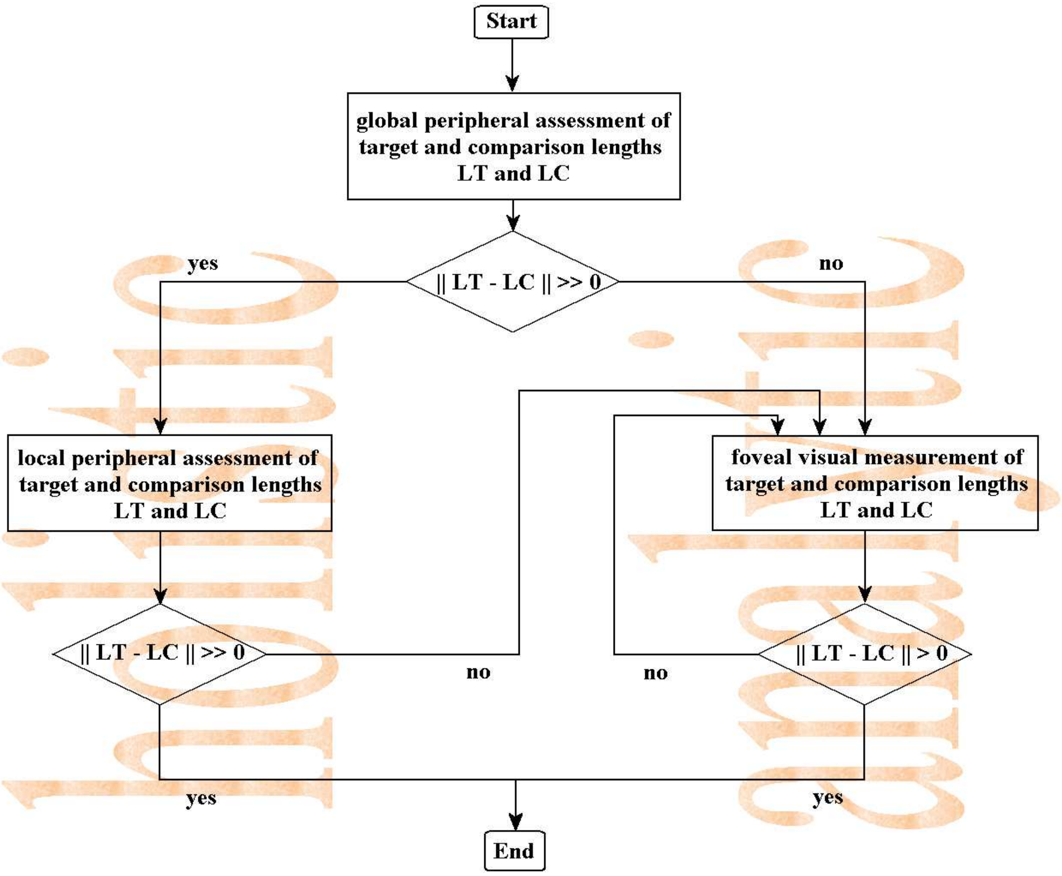


Figure 12.1: Schematic illustration of the basic concept for modelling similarity effects during the simultaneous assessment of line segment lengths.

results for the number of saccades between hemifields SB. On the other hand, the simulation would yield significantly more correct discrimination results than the empirical data (compare the dependent variable discrimination correctness DC in Section 11.3).

Figure 12.1 illustrates the fundamental components of the model concept that is implemented to accomplish the simultaneous length discrimination task.

Yet again, this modelling approach must "prove" its correctness. Only then can we assume that it supports the correctness of the assumptions, suggests an appropriate explanation that accounts for the major empirical observations and adequately simulates the visual strategies and the corresponding eye-movement parameters. The following section describes the (algorithmic) model implementation which aims to yield the desired support.

12.3 Model Implementation

The presentation of the model concept only yields a rather abstract description of its realisation. In order to implement the modelling approach in algorithmic form, the computational steps must be discussed. By partially integrating the relevant mechanisms that have been established when modelling eccentricity effects in Chapter 8, the following procedure to accomplish the implementation of the proposed model will be pursued in principle (for details see the previous Section 12.2):

(a) Initial, pre-attentive peripheral length assessment of both the target and the comparison line segments, viewed from a fixation point at the display center. Additional peripheral assessment of the target orientation. Implementation according to the algorithm for simulating the lengths and orientations of peripherally perceived line segments as introduced when modelling eccentricity effects (see Section 8.2.2, page 117).

(b) Comparison of the two line segment lengths simulated in (a).

(c) Switch to holistic visual processing mode in case the comparison yields a "significant" length difference. Otherwise, switch to analytic mode.

(d) Determine "landmark" point at which the following saccade aims:

· Holistic: Usually that end point of one of the line segments which is closest to the current fixation point. The mid point of the line segment may be chosen in some cases, in particular for fixations on oblique or vertical targets.

· Analytic: That end point of one of the line segments which is closest to the current fixation point.

(e) Simulate the peripheral assessment of the location of the landmark point of (d) according to the eccentricity model procedure, thus determining the (location of the) landing point of the saccade.

(f) Execute a saccade from the current fixation point to the saccade landing point simulated in (e).

(g) Holistic:

· Peripherally assess the location of the second end point of the line segment, again according to the eccentricity model procedure.

· Compute the distance between the current fixation point and the modelled location of the second end point as the locally peripherally perceived length of the line segment. No saccade is executed to visually measure this length or a fraction thereof.

· When the current fixation point is "on“ (better: in proximity to) the mid point of the line segment (see above), peripherally assess both end points analogously. Add the distances between the midpoint and the two end points to obtain the line segment length.

· When the target and comparison line segments have intermediate or long length and are not co-linearly oriented, switch to local analytic processing to visually measure the length, executing a "measuring saccade" (see "(h) Analytic" below).

- Memorise length representation. The representation accuracy deteriorates over time.
- Shift attention to the other line segment and assess its length analogously: Re-iterate steps (d)—(g).
- Compare the representations of the two line segment lengths that were simulated by local peripheral assessment mechanisms.
- If the comparison yields a significant length difference, choose the respective longer line segment to generate a corresponding response and terminate the trial. Otherwise, re-iterate steps (d)–(g).

(h) Analytic:

- Peripherally assess the location of the second end point of the line segment according to the eccentricity model procedure.
- Compute the distance between the current fixation point and the modelled location of the second end point as the locally peripherally perceived length of the line segment. Divide this distance by two to obtain the length of the subsequent saccade that attempts to visually measure half the perceived length of the line segment.
- Execute the measuring saccade. Its direction aims at the peripherally assessed end point of the line segment.
- Evaluate the distances from the new fixation point to both end points of the line segment, using the peripheral location assessment model. If they are not about equal, adjust the representation of the saccade length accordingly. This update improves the representation that the visual measurement process yielded. A corrective saccade is not usually executed – unless the currently fixated point is "too distant" from the mid point of the line segment.
- When the line segments are short, the peripheral assessment and fraction representations are not required. Instead, the two end points of the line segment are foveally assessed. A measuring saccade is executed from the modelled location of one end point to that of the other. The landing point of the saccade can be modelled accordingly within the accuracy of location estimations in the eccentricity region I (see Experiment E0). The entire length of the connecting measuring saccade represents the length of the line segment.
- Memorise the length representation. The representation accuracy deteriorates over time.
- Shift attention to the other line segment and assess its length analogously: Re-iterate steps (d)—(f) and (h).
- Compare the two line segment length representations that were simulated by fractional visual measurement.

· If the comparison yields a "significant" length difference, choose the respective longer line segment to generate a corresponding response and terminate the trial. Otherwise, re-iterate steps (d)–(f) and (h).

These steps of the abstract "algorithm" have to be computationally implemented. Let us now consider this implementation task in detail.

12.3.1 Peripheral Assessment and Representation

The list of procedural steps stipulates once again that quite a large number of processes involve the peripheral assessment of locations and lengths. The assessment of such visual information in certain eccentricity regions appears to be important not only in holistic mode, but also for the analytic assessment of line segment length. Peripherally perceived location information is "directly" integrated into the length computations in holistic mode when the discrimination task is easy and length assessment is denoted a local peripheral process. When line segments have to be foveally scanned to judge lengths in analytic mode, peripherally acquired data is also essential to determine saccade landing points or, more general, for saccade planning and execution.

Conveniently, the respective algorithms to formalise such peripheral location and length assessment processes were already implemented to develop the eccentricity model in Chapter 8. The distributions of estimates for target marker locations in different eccentricity regions in Experiment E0 were parameterised, using principal component analysis (PCA), and then simulated, using the probabilistic Monte Carlo simulation model. When these mechanisms were applied to model the locations of end points of line segments, the subsequent computation of the distance between the simulated end points quite accurately yielded the same lengths of line segments as when subjects peripherally assessed line segment lengths. Consequently, these algorithms will be re-used here to formalise the peripheral assessment aspects in the current similarity model implementation.

Saccade Planning Essentials

The peripheral modelling processes and their conjunction according to the *decomposition/fusion* hypothesis can account for several other aspects of the proposed similarity model. Apart from the global and local peripheral assessment of line segments, peripheral end point assessment is essential for saccade execution. Before details of saccade planning and execution can be discussed (see Section 12.3.2), the saccade planning essentials will be considered.

The determination of a "landmark" point that a saccade aims at is of particular interest here. Although the decomposition hypothesis already suggests that end points of line segments are likely "candidates", it must still be determined which of the end points a saccade aims at. With regard to the global (inter-hemifield) saccade planning, a "nearest-neighbour" approach appears reasonable. With the current fixation point

$$P_t = \{\vec{p}_{fix}\} \qquad (12.1)$$

the according landmark point for the current fixation

$$L_t \quad = \quad \{\vec{l}_{fix}\} \tag{12.2}$$

and the end points (of the other stimulus constituent) that serve as possible landmark "candidates" for the subsequent saccade

$$L_{t+1} \quad = \quad \{\vec{l}_i\};\ i = 1, .., n \tag{12.3}$$

minimising the (Euclidean) distance d according to

$$d_{min}(P_t, L_{t+1}) = \min_i \|\vec{p}_{fix} - \vec{l}_i^{\,\prime}\| \qquad \text{where} \quad \vec{l}_i^{\,\prime} \in L_{t+1} \setminus L_t \tag{12.4}$$

yields the innermost end point of the line segment in the other stimulus hemifield as the preferred candidate for the subsequent fixation when inter-hemifield saccades are to be executed. This (initial) choice of the nearest-neighbour algorithm is then subject to post-processing by a probability function in order to introduce a certain amount of "noise". This allows some saccades to aim at the outermost end point of a line segment – as found in the empirical data. Rather than always selecting the nearest neighbour, i.e. the innermost end point, the algorithm can also choose the outermost end point of the line segment in the other stimulus hemifield as the landmark for the saccade landing point with a rather small probability. The probability function will be further tuned so as to yield outermost end points more often when attention shifts from the target to the comparison hemifield than vice versa. To account for mid-point fixations after shifts of attention between hemifields, a certain percentage of saccades will also aim at those landmark points.

For the simulation, the observed empirical distributions of the ratios/percentages of fixations that aim at the innermost or outermost end points of a line segment or at its mid-point will be approximated. This can be achieved using distributions which can be exactly described mathematically using probability functions. For the current discrete probability distributions, a discrete multinomial (or polynomial) probability function is required:

$$\begin{aligned} f(k_1, k_2, ..., k_s | n, p_1, p_2, ..., p_s) &= \\ \frac{n!}{k_1! \cdot k_2! \cdot ... \cdot k_s!} \cdot (p_1)^{k_1} \cdot (p_2)^{k_2} \cdot ... \cdot (p_s)^{k_s} &= \\ \frac{n!}{\prod_{i=1}^{s} k_i!} \cdot \prod_{i=1}^{s} (p_i)^{k_i} & \qquad \text{where} \end{aligned} \tag{12.5}$$

$1, 2, ..., s$	are the different "events" (innermost, outermost, mid-line landmark point), i.e. $s = 3$,
n	is the number of (simulation) trials,
$k_1, k_2, ..., k_s$	are the numbers of observations for the different events and
$p_1, p_2, ..., p_s$	are their probabilities.

It should not go unmentioned that, for $s = 2$, Equation 12.5 is reduced to the well-known formula that yields the probabilities for a binomial distribution:

$$f(X = k|n) = \binom{n}{k} \cdot p^k \cdot q^{n-k} \qquad \text{where} \tag{12.6}$$

$f(X = k\|n)$	is the probability for the random variable X to be of value k when n independent (Bernoulli) trials are conducted and $p + q = 1$.

Equation 12.5 yields the probability distribution of the different events, occurring with a certain probability, which can be observed after a specific number of trials. Consequently, using Equation 12.5 with the probabilities for p_1, p_2 and p_3 as computed from the subject data – for choosing innermost, outermost or mid-line landmark points, respectively – produces probabilities whose multinomial probability distribution simulates the empirical one.

12.3.2 Foveal Assessment and Representation

This approach to integrate "controlled" noise, based on observed empirical uncertainty, into the saccade planning model may not only be used to affect the simulation of the global strategy level. Such an approach also appears to be promising in order to enable the model to adequately account for specific empirical observations on the local processing level. Analogous probability functions will be used now to approximate the characteristic distributions found in the subjects' data regarding when or how often more successive fixations occur in an attempt to visually measure a line segment – compared to the common pattern in analytic mode of two successive fixations on a line segment preceding attention shifts to the other display hemifield. However, rather than depending entirely on such probabilistic mechanisms, most parameters that determine the implementation of the saccade planning model are influenced by other factors.

As the most relevant factors, the model will take into account the attributes of the line segments, i.e. their lengths and orientations relative to each other. Furthermore, primarily data from the last fixation/saccade and the accuracy of the current/previous visual measurement, i.e. the current state of the mental representation so far generated by the model implementation, will affect saccade planning and length representation generation and update. The principle the current model uses for saccade planning in analytic mode is similar to the basic implementation of the peripheral visual length assessment of a line segment in holistic mode. This model aspect will thus be implemented according to the algorithm presented in Chapter 8 for modelling eccentricity effects. However, several adaptations have to be made in this case. These adaptations are required, for example, as otherwise the foveal visual measurement in analytic mode would result in the same accuracy as the peripheral length assessment in holistic mode: It must be expected that subjects consider foveal scanning and visual measurement as being more accurate than peripheral length assessment as they shift to analytic mode in case the assessment task becomes more difficult. To account for this improvement in the assessment accuracy, the model algorithm will perform an "evaluation" of the location of the second fixation of a measuring saccade.

Let us recall that initially the landing point of a measuring saccade is computed as being located at about half the distance between the first fixation on the line segment – in proximity to one end point – and the peripherally assessed other end point (when line segments have intermediate or long lengths). After this measuring saccade has been executed, the location of its landing point can now be evaluated with respect to the (physical) mid point of the line segment. The evaluation will be implemented as peripherally assessing the two end points of the line segment, viewed from the landing point of the measuring saccade. This should be achieved more accurately with the locations to be assessed now only being half as distant as for the initial assessment, yielding the peripherally perceived length of each half of the line segment. If a significant difference between these two perceived lengths is found, the length representation based on the previously executed measuring saccade will be adjusted accordingly. However, a corrective saccade will not be executed, only the mental model representation will be adapted.

The evaluation and amendment mechanism is only implemented for line segments that have intermediate or long lengths. Another evaluation mechanism attempts to also improve the accuracy of length assessments for short line segments. It is based on the repeated visual measurement of line segment length while no intermediate shifts of attention to the other hemifield occur. This mechanism will also be used to further improve the assessment accuracy of longer line segments – if required. After visually measuring a line segment once, the algorithm will compute a saccade back to the previously fixated end point of the line segment – the equivalent to the "alternating saccades" observed in the empirical data. Having previously stored the location of that point along with additional information on the location deviation from the physically correct location of that end point, the backward saccade will be able to more accurately measure the length of the line segment or the respective fraction than the previous measuring saccade. This will be implemented as a reduction of the standard deviations of the bivariate normal distribution

$$\phi_N(x,y) = \frac{1}{2\cdot\pi|\Gamma|^{\frac{1}{2}}} \cdot e^{-\frac{1}{2}\left[\begin{smallmatrix} x-\mu_x \\ y-\mu_y \end{smallmatrix}\right]^T \Gamma^{-1} \left[\begin{smallmatrix} x-\mu_x \\ y-\mu_y \end{smallmatrix}\right]} \tag{12.7}$$

that describes the distribution of the location assessments in that specific eccentricity (see Section 8.2.2, Equation 8.6). The current standard deviations σ_x and σ_y will be reduced so that the deviation $\vec{d}$ of the previously stored location of the fixation (x, y) from the distribution origin (μ_x, μ_y)

$$\vec{d} = \begin{pmatrix} x \\ y \end{pmatrix} - \begin{pmatrix} \mu_x \\ \mu_y \end{pmatrix} \tag{12.8}$$

now yields $\sigma_x^{'}$ and $\sigma_y^{'}$ so that

$$\phi_N(\vec{d}) = \phi'_N(\vec{d'}) \qquad \text{where} \tag{12.9}$$

$$\vec{d'} = 2 \cdot \begin{pmatrix} \sigma'_x \\ \sigma'_y \end{pmatrix} \qquad \text{with} \tag{12.10}$$

$$\frac{\sigma'_x}{\sigma'_y} = \frac{\sigma_x}{\sigma_y} \tag{12.11}$$

This yields a bivariate normal distribution that preserves the ratio of its principal components, but has its standard deviations reduced so that approximately 95.5% of the function values are closer to its origin than the previously fixated location was. The subsequent computation of the Monte Carlo Simulation will thus produce fixation points that with a very high probability are located closer to the actual landmark point (one of the line segment's end points or its intermediate point) than before. This improvement can be observed with every iteration, i.e. with every repeated visit to a previously visited location.

In contrast to improving the assessment accuracy over repeated visits or when alternating saccades occur, the model should yield less accurate length estimates when a line segment is visually measured by three successive fixations that are oriented "in line". On first sight, this appears contradictory to the previous paragraph where it was argued that three successive fixations rather improve the assessment accuracy. However, we must consider that the alternating saccade "updates" an already existing length representation, yielding additional data that amends the representation by improving the accuracy of the location of end points. In contrast, all three "in line" fixations contribute to the initial, step-by-step generation of a length representation; the second saccade does not serve a validation function. It thus appears to be plausible that the deterioration of the assessment accuracy may be caused by more complex mental processing steps and the need to integrate more data into the computation of length. In fact, subjects most frequently produce such a pattern for "complex" configurations when the line segments to be assessed are long and not co-linearly oriented so that a mental rotation of a stimulus may be required whose overall length can only be assessed peripherally. Using the above-mentioned multinomial probability function that approximates the empirical distribution of how often three successive in-line fixations occur (in relation to the usual two-fixation visual measuring or an alternating fixation pattern) for a specific stimulus configuration (defined by line segment lengths and orientations determined during the initial global peripheral assessment of the line segment), the model should be able to apply this fixation pattern in an adequate number of cases.

The model can now quite naturally reflect the pattern itself along with its associated length representation effects in according computational steps: Using the "usual" peripheral location assessment algorithm to determine the distance between the current fixation point in proximity of one end point of the line segment and the other end point, this distance now has to be divided by four (see Section 12.2) to yield the location at which the first of the two successive saccades aims. If we consider that this "computation" might be accomplished by mentally intersecting the peripherally assessed overall length of the line segment twice, each of these processing steps can be assumed to aggravate the location accuracy. Although the end point already peripherally assessed can now be re-assessed from a less peripheral position (the new fixation point), improving the location assessment accuracy and thus the distance assessment, the subsequent division is even more complicated. To yield about half the overall length of the line segment, the newly assessed distance has to be divided by three. This process cannot be simplified by re-iterating mental intersections at half the distance as previously for divisions by four. Furthermore, the two odd length representations must be added to yield the desired length representation. It must further be assumed that the representation of the length of the first saccade has already deteriorated in the meantime. In addition, the outlined procedure generates concurrent memory representations. This may result in an even more pronounced memory decay.

The model will account for these effects by adding "noise" to each division process. This will result in each line segment fraction, irrespective of whether it is visually measured by two or three successive fixations, not being divided by exactly two or three, respectively. In order to account for the effects of the horizontal-vertical illusion (target length overestimation in Experiment S1), the "noise function" should not simply be Gaussian. Instead, an asymmetrical function with a positive skewness and centered at the respective correct dividend (two or three) should be chosen. A distribution that meets these requirements is the χ^2 (Chi-Square) distribution. It results when df independent variables $z_i, i = 1, ..., df$ with standard normal distributions are squared and summed:

$$\chi^2_{df} = z_1^2 + z_2^2 + ... + z_{df}^2 = \sum_{i=1}^{df} z_i^2 \tag{12.12}$$

df is referred to as the degrees of freedom or "shape factor" of the χ^2 distribution. The χ^2 distribution has the properties

$$\begin{array}{rrcl} \text{mean} & \mu & = & df, \\ \text{standard deviation} & \sigma & = & \sqrt{2 \cdot df}, \\ \text{skewness} & \gamma & = & 2^{\frac{3}{2}}/\sqrt{df} \\ & & = & 2 \cdot \sqrt{2/df} \end{array}$$

and its shape can be described by the following probability density function:

$$\phi(\chi^2) = \frac{1}{2^{\frac{df}{2}} \cdot \Gamma(\frac{df}{2})} \cdot e^{-\frac{1}{2} \cdot \chi^2} \cdot (\chi^2)^{\frac{df}{2}-1} \tag{12.13}$$

where Γ is Euler's Gamma function with

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} \cdot e^{-t} dt \tag{12.14}$$

Generating values that show such a probability distribution will, on average, produce dividends smaller than two (or three) as the median is smaller than the mean μ. This yields larger fraction representations of the target line segment (which is often visually measured by three successive fixations when it is not co-linearly oriented with the comparison line segment) than according representations of the comparison line segment. Thus the comparison representation will be considered too short or, in other words, the target length is overestimated. While for divisions by three a "noise function" with a higher positive skewness and a larger standard deviation than for divisions by two will be introduced, the division by four will be implemented as two iterated divisions by two, thus yielding less accurate results. Figure 12.2 illustrates several χ^2 distributions and shows that their probability distributions indeed produce the intended effects of larger variances for higher degrees of freedom, i.e "more noise" when $df = 3$ (division by three) than when $df = 2$ (divisions by two).

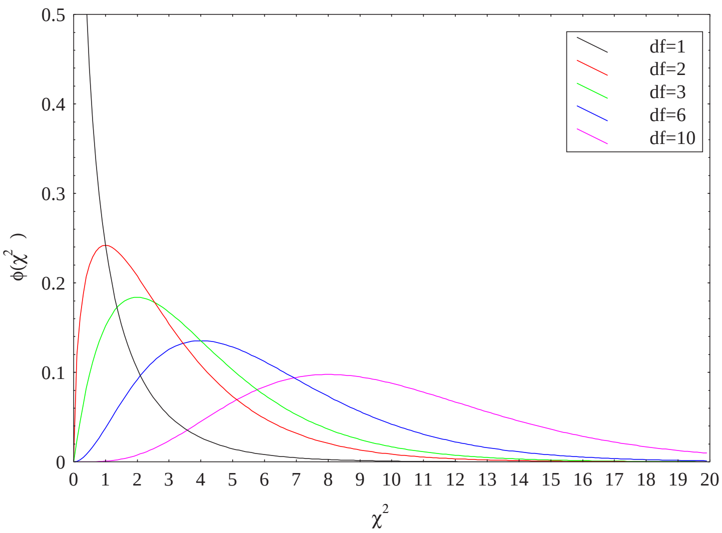


Figure 12.2: Density distributions of χ^2 distributions for different degrees of freedom.

12.3.3 Memorisation

In order to model memory "loss" over time, a decay function is implemented. It takes into account the durations of all fixations that occurred within each hemifield during the generation of the mental representations. Consequently, the observation of more numerous fixations plus the assumption that the more complex computations to integrate more complex data into a length representation take longer, both increase the memory loss. The representation accuracy thus decreases and makes the result of the discrimination task more prone to error. This model implementation also adds to the illusory effects of the horizontal-vertical illusion. With the assessment of an oblique or vertical target line segment requiring more fixations and the subsequent data integration taking longer, the decay of the target length representation will be more pronounced. The model interprets decay as a slight increase in the represented length (which is in line with the observations in Experiment E1 where lengths of peripherally perceived and memorised targets were overestimated). This decay is represented along a logarithmic (decay) function (see Ebbinghaus, 1885/1964)

$$LT(t) = LT_0 \cdot (1 + e^{-\frac{n(t)\cdot \overline{FD}_{o,l}}{t}}) \tag{12.15}$$

where

$LT(t)$	is the representation of the assessed target length at time t
$LT_0 = LT(t = 0)$	the representation of LT at the time of the first (peripheral) assessment
$n(t)$	n the number of fixations so far, and
$\overline{FD}_{o,l}$	the mean fixation duration for the present factor combination of line segment length and orientation,

yielding longer target lengths at comparison time than when initially perceived. This can also be used to model the overestimation of target line segment length in the dynamic adjustment scenario of Experiment S1.

To be able to model this time-dependent decay function, the fixation duration must also be adequately represented in the model. This will be achieved by approximating the distributions of fixation duration FD for the various factor combinations of target line segment length (l) and orientation (o) by Gaussian distributions

$$\phi(FD, l, o) = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma_{l,o}^2}} \cdot e^{-\frac{(FD-\mu_{l,o})^2}{2\cdot\sigma_{l,o}^2}} \tag{12.16}$$

taking their means $\mu_{l,o}$ and standard deviations $\sigma_{l,o}$ from the empirical data. Again, using Monte Carlo simulation to select FD for modelling while respecting the corresponding parameterised distributions, it can be assumed to simulate adequate time-dependent memory decay functions as well as to reproduce the empirical values for the fixation times.

12.3.4 Comparison and Matching

Let us finally consider again the global modelling aspects. We must assume that multiple visits to the two stimulus constituents improve the assessment accuracy. In analogy to updating and thus amending length representations by alternating intra-stimulus saccades (see previous paragraphs), a similar mechanism can be implemented to account for the representation update during various shifts of attention between hemifields. Although some representation accuracy is lost again during inter-stimulus saccades due to memory decay, the model approach will account for repeated visits to the same stimulus regions, i.e. its end and intermediate points, by moving the fixation closer to the physical location of the landmark point a saccade is aimed at and should thus improve the length assessment accuracy compared to the initial assessment. This will be implemented as a reduction of the standard deviations of the bivariate normal distribution that describes the distribution of the location assessments at that specific eccentricity. The implementation follows the principles as lined out for the improvement of the assessment accuracy when alternating saccades occur. The algorithm applied then to model the adaptation of the standard deviations during intra-hemifield processing can be taken over for re-use here. The Equations 12.7 – 12.11 mathematically describe the required algorithmic processing steps. These adaptations of the bivariate normal distribution will result in the subsequent computation of the Monte Carlo Simulation to produce fixation points that move closer to the actual landmark point, namely the line segment's end or intermediate point with every iteration, i.e. with every repeated visit to that hemifield.

This leaves only few questions regarding the algorithmic implementation of the model unanswered. It must, for example, be determined which differences in the length representations will be considered as being large enough to reliably decide which of the two line segments is longer. In accordance with the length differences that were established in Experiment S1 to distinguish between easy and difficult discrimination tasks in the following Experiment S2, a minimum distance of $(4 \cdot \sigma_{LC_{S1}})$ (see Section 11.1) will be used, $(\sigma_{LC_{S1}})$ varying for the different factor combinations of target line segment length and orientation. If a difference less than that is found between the target and the comparison lengths after the first local peripheral length assessment in holistic mode, the "first" line segment will again be assessed locally peripherally. Should this not allow for a reliable discrimination, one of the line segments will be foveally measured in a further step. If then still no reliable discrimination result emerges, the model completely shifts to analytic mode and proceeds with the typical procedure for that task difficulty as sketched. The criterion for a reliable length discrimination must be set differently in analytic mode. As the physical lengths between target and comparison differed by $(1 \cdot \sigma_{LC_{S1}})$, the model terminated when the simulated length representations yielded at least such a minimum difference.

Finally, the model must be prevented from shifting attention between hemifields too often. If this is not being accounted for, the simulation can be expected to produce a higher number of correct discrimination results than the empirical data. This is due to the fact that the assessment accuracy of the model improves with each repetition. A maximum number of SB of between three and five, randomly chosen, is thus introduced. However, for most model trials, the comparison should terminate before reaching this "artificially" imposed limit.

Based on Figure 12.1, Figure 12.3 now illustrates the computational model for simultaneous line segment length assessment and comparison in more detail. The next section shows the results that the algorithm yielded and discusses its performance, based on the results of a statistical analysis, in relation to the empirical data.

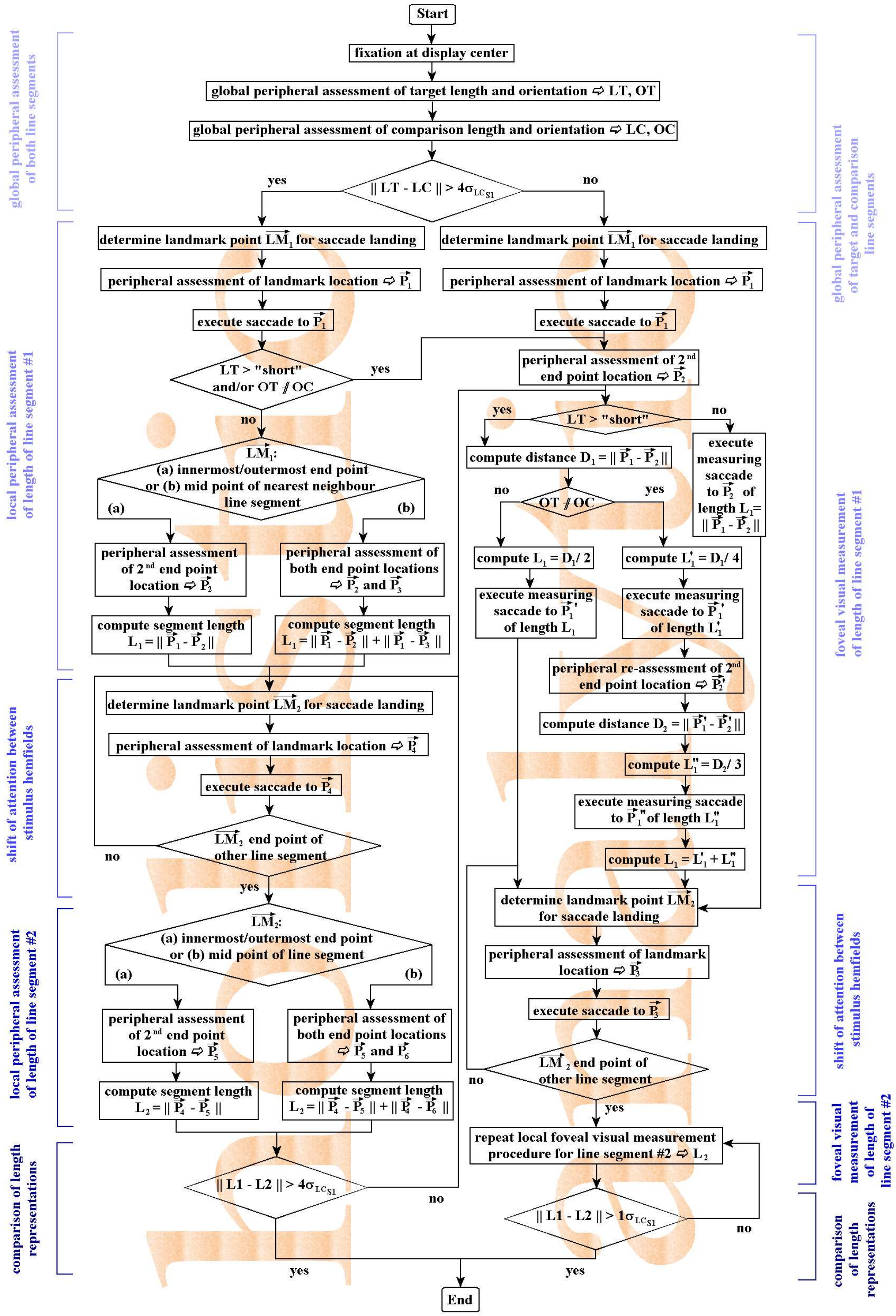


Figure 12.3: Detailed illustration of the model implementation for the simultaneous assessment of line segment lengths.

12.4 Model Results and Discussion

Analyses of variance were computed to establish the effects of the factors discrimination difficulty, target line segment length and target line segment orientation on the model discrimination correctness MDC and the same eye-movement parameters that already constituted the dependent variables in Experiment S2. In addition, the corresponding mean values for the various factor levels were computed. Introducing the between-subjects factor "experiment", i.e. Experiment S2 vs. simulation, the direct comparison of the empirical and simulated data allows us to validate whether the model correctly accounts for the effects and their magnitudes established in Experiment S2. For the sake of clarity of the presentation, data visualisation in particular focuses on this comparison. Due to the large number of dependent variables – compared to the investigation of eccentricity effects – the separate charting of means for the model variables as in Section 8.3 is not recommended.

In addition, the model implementation produced the perceived lengths of the target and comparison line segments, so that the length deviations DL could be computed. The comparison of this model-generated data with the respective empirical values thus further allows us to validate if the model could also account for the visual illusory effects found in Experiment S1 – although the model did not implement the dynamic adjustment procedure of that experiment.

The model data was computed according to the previously described modelling procedure and constituted data sets of the same structure as recorded in Experiment S2. Furthermore, data was simulated for the same combinations of the factors discrimination difficulty, target line segment length and orientation. The number of repeated measures and (here "virtual") subjects was also identical in order to ensure equal conditions for the comparison of the simulated and the empirical data sets.

Model Discrimination Correctness MDC

Let us first see how the model "scores" in the discrimination task, i.e. how successfully it correctly identifies the longer of the two line segments presented – and how MDC compares to the empirical DC.

The four-factorial analysis of variance of the factors experiment, discrimination difficulty, target line segment length and orientation yields no significant main effect of the factor experiment on the discrimination correctness ($F(1;66) = 0.21; p = 0.646$), indicating that the model algorithm succeeds in reproducing similar ratios of correct and incorrect answers in the discrimination task. This high correlation between the empirical and the model data (see Figure 12.4, easy discrimination) could certainly have been expected in case of the easy discrimination condition. Here, the model implementation largely relies on (local) peripheral processing and is based on the successful eccentricity modelling approach. This model has already demonstrated (see Chapter 8) that it can quite accurately assess the length of line segments presented in the peripheral visual field. With the length differences of the two simultaneously presented line segments being considerably larger than the accuracy of the eccentricity model, the high model rate of almost

100% correct answers (MDC $\cong$ 1.0) is not surprising.

However, the model algorithm sometimes applied the analytic processing mechanisms for certain factor combinations of target length and orientation even when the discrimination task was labelled "easy". The observation that in such cases, in particular when long, not co-linearly oriented line segments had to be assessed, the model data still yields highly correct responses (as subjects also do) can be regarded as initial support for a good performance of the model in analytic mode as well. The model implementation based on foveal visual measurement of line segments obviously yields quite accurate length assessments which allow for an almost perfect discrimination performance – at least for easy discrimination tasks when the physical lengths of the line segments are significantly different. Furthermore, the close correspondence between DC and MDC persists when the discrimination task is difficult. Although the curves for DC and MDC in Figure 12.4 are not quite as close as those for the easy discrimination condition, the statistical analyses point to a convincing model performance in analytic mode as well.

The only two-way interaction that reaches significance is that between experiment and orientation ($F(2; 132) = 4.13; p = 0.018$) and indicates that the model may not entirely account for the differences in (M)DC that exist in the empirical data between obliquely and vertically oriented targets: Whereas DC significantly decreases from 0.80 for oblique to 0.73 for vertical targets (Newman-Keuls: ($R_{crit} = 0.106; p = 0.035$)), MDC does not, but remains almost constant at 0.77 and 0.78, respectively. A Newman-Keuls post-hoc test reveals that no significant difference exists in MDC between these two factor levels ($R_{crit} = 0.076; p = 0.152$). Interestingly in this context, the three-way interaction between experiment, target orientation and discrimination difficulty also reaches significance ($F(2; 132) = 4.95; p = 0.008$). This apparently originates from MDC differing from

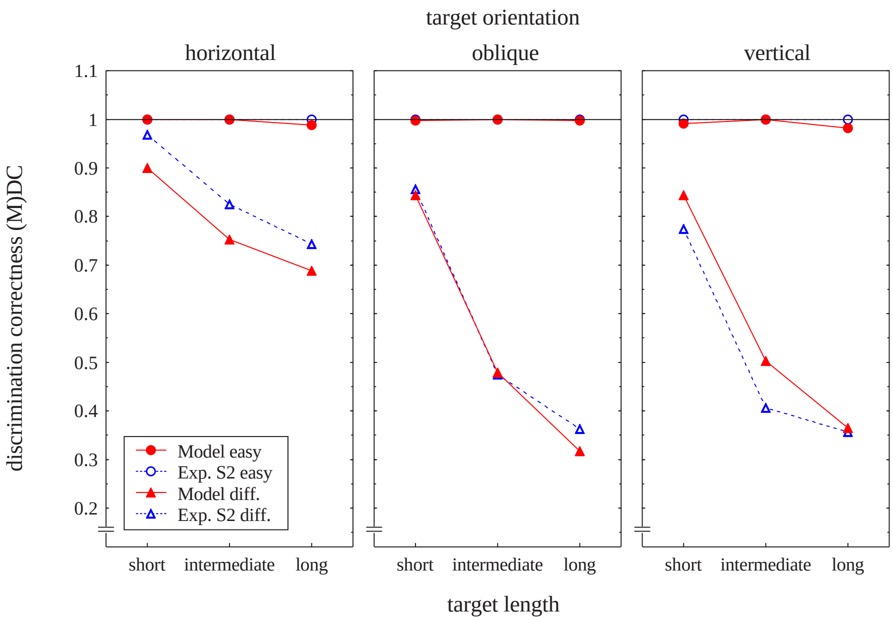


Figure 12.4: Comparison of the empirical and simulated discrimination correctness DC (blue dotted) and MDC (red solid) for the target line segment lengths (short, intermediate, long) and orientations (horizontal, oblique, vertical) when the discrimination task is easy (circles) and difficult (triangles).

DC between the oblique and vertical target orientations only when the discrimination task is difficult. It thus appears possible that the model is well able to adopt its processing mechanisms in analytic mode to account for co-linearly and not co-linearly oriented line segments differently – and in accordance with the empirical data.

However, the model algorithm may still have some deficits in making finer distinctions between different tilted line segments, i.e. to distinguish between oblique and vertical, for example. As no other differences between DC and MDC become significant and, in general, means of MDC very closely resemble those of DC, the chosen model implementation can still be considered promising in this respect so far. Figure 12.4 qualitatively supports this statement and shows the means of the empirical data of Experiment S2 in comparison with those of the similarity model as a function of target line segment length. In order to improve the clarity of the illustration, the values are charted separately for the three target orientations horizontal, oblique and vertical.

Model Reaction Time MRT

The model implementation does not explicitly simulate reaction time. Rather, MRT, the modelled reaction time, can be implicitly computed from the modelled fixation duration MFD (see later in this section). Rather than only summing up all MFDs per trial, saccade durations must also be added to yield MRT. With saccade "velocity" remaining almost constant in the empirical data, independent of saccade length, saccade duration is calculated as

$$\text{saccade duration} = \frac{\text{saccade length}}{\text{saccade velocity}}$$

and added to MRT for each saccade executed. It must be noted that this equation is a simplification which assumes that saccade velocity remains constant *during* a saccade. In reality, this is not the case.

The four-factorial analysis of variance yields no significant main effect of the factor experiment on the discrimination correctness ($F(1; 66) = 10.21; p = 0.142$), indicating that the model-generated reaction times MRT in general are quite similar to those that the subjects produced in Experiment S2. The comparison of means (see Figure 12.5) shows that for both the easy and the difficult discrimination condition MRT is longer than RT. Although not significant, it appears that the model algorithm generates slightly more fixations and saccades than subjects – or that FDs are longer in the model than in the empirical data. The differences between MRT and RT are most pronounced when long, not co-linearly oriented line segments are presented. A deficit of the model to correctly reproduce FDs thus appears less likely, otherwise probably all MRTs should have been prolonged equally. Furthermore, FDs have been modelled based on the distributions of the empirical data, taking into account the individual differences of those for the various factor combinations. The FD-model should thus be quite accurate (see later in this section, "Fixation duration MFD"). Instead, when the discrimination is easy, the model may "too soon", i.e. too often, switch from holistic into analytic mode. This generates more fixations and saccades and thus increases the overall MRT. When the model pursues the analytic strategy for difficult discrimination tasks already, the increased MRTs may be caused by

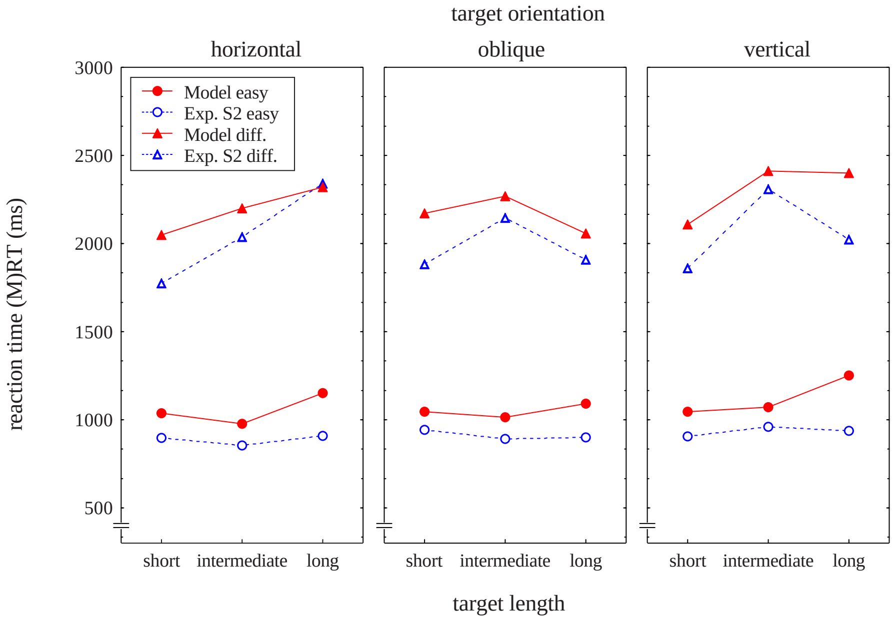


Figure 12.5: Comparison of the empirical and simulated reaction times RT (blue dotted) and MRT (red solid) for the target line segment lengths (short, intermediate, long) and orientations (horizontal, oblique, vertical) when the discrimination task is easy (circles) and difficult (triangles).

too many shifts of attention between display hemifields and/or a slightly higher rate of three successive fixations within the same hemifield for such a factor combination. The analyses of the respective variables later in this section should clarify these considerations.

In this context, the only significant interaction effect on (M)RT involving the factor experiment, namely that between experiment, target length and orientation ($F(4; 264) = 2.98; p = 0.020$), must be considered. A post-hoc comparison of means using the Newman-Keuls test reveals that significant differences indeed exist ($R_{crit} = 168.03; p < 0.001$) between the model and the empirical data when the length of long vertical targets has to be assessed. The analysis does not yield any other significant interactions between the model and Experiment S2. Figure 12.5 shows the RT means of Experiment S2 in comparison with MRT of the similarity model as a function of target line segment length. In order to improve the clarity of the illustration, the values are charted separately for the three target orientations horizontal, oblique and vertical. The two resembling curves for each factor combination visualise the good correspondence between model and experiment with respect to reaction time and thus are in line with the statistical results.

Model Number of Fixations MNF

After the statistical comparisons of the empirical and the model results have demonstrated a high correlation between those two data sets with respect to the more "conventional" variables (M)DC and (M)RT, the eye-movement parameters must now be addressed.

Most of the comparisons of the numbers of fixations do not produce a significant difference between the empirical and the model results. Four-factorial analyses of variance do not yield such an effect for the overall numbers of fixations (M)NF ($F(1; 66) = 1.03; p =$

0.313), the numbers of fixations in proximity to the target (M)NF$_T$ ($F(1;66) = 10.21; p = 0.142$), or those in proximity to the comparison (M)NF$_C$ ($F(1;66) = 10.21; p = 0.142$). The only significant interaction affected by the comparison between Experiment S2 and the model is that between the factors experiment, target length and orientation. The analysis of variance yields ($F(4;264) = 3.08; p = 0.049$) for (M)NF and ($F(4;264) = 1.79; p = 0.032$) for (M)NF$_T$ for these three-way interactions; none was found for (M)NF$_C$. A closer inspection of Figure 12.6 reveals that there indeed appears to be a difference between the empirical and the model data when targets are obliquely oriented. Both charts for (M)NF and (M)NF$_T$ show that these numbers of fixations slightly increase from short through intermediate to long targets in the model whereas the empirical data remains almost constant for the different lengths (or even slightly decreases). This is in particular visible in the difficult discrimination condition. Quantitatively, this is supported by a post-hoc comparison of means using the Newman-Keuls test that identifies the already (quantitatively) noted differences – and only those – as being responsible for the significant interaction effect: The test computes ($R_{crit} = 0.82; p = 0.025$) and ($R_{crit} = 0.89; p = 0.019$) for the differences between the empirical and the model data in (M)NF for oblique targets when their lengths are intermediate and long, respectively, and ($R_{crit} = 0.69; p = 0.047$) for the differences between the empirical and the model data in (M)NF$_T$ for oblique targets when their lengths are long.

With regard to the number of fixations in the intermittent display section, MNF$_I$ is significantly higher than NF$_I$ and the four-factorial analysis of variance produces a significant main effect for the factor experiment ($F(1;66) = 1.22; p = 0.015$). As for the other categories of the numbers of fixations, the model values are higher than those measured in Experiment S2. In case of (M)NF$_I$, the difference is now a significant one, Figure 12.7 (bottom) illustrates the apparently large differences. However, the absolute differences are not quite as drastic as they appear. In order to visualise the individual differences, the vertical scale is of a different order of magnitude compared to those for (M)NF, (M)NF$_T$ and (M)NF$_C$. Thus, the largest (absolute) difference between empirical and model data only measures 0.2 fixations. As the model algorithm does not explicitly distinguish between holistic and analytic mode when executing intermittent fixations, it is not likely to find the same differences in the model data as in the empirical data. However, MNF$_I$ is implicitly influenced by the planning of inter-stimulus saccades. Since in holistic mode a larger percentage of such model saccades aim at the center or outermost point of the line segment in the other display hemifield than in analytic mode, the distance between the current and the subsequent fixation point is longer in the first case. The assessment of more peripheral points will consequently be less accurate and will lead, according to the model implementation, to the execution of intermittent fixations more often when the discrimination is easy. On the other hand, more shifts of attention between hemifields should occur when the discrimination is difficult. This would then increase the number of intermittent fixations in that processing mode, so that the rather equal values for MNF$_I$, irrespective of the discrimination difficulty, can be understood. Following the same argumentation, it is clear that the model adequately reproduces the effects of target length and orientation on NF$_I$: Line segments that are not co-linearly oriented are further

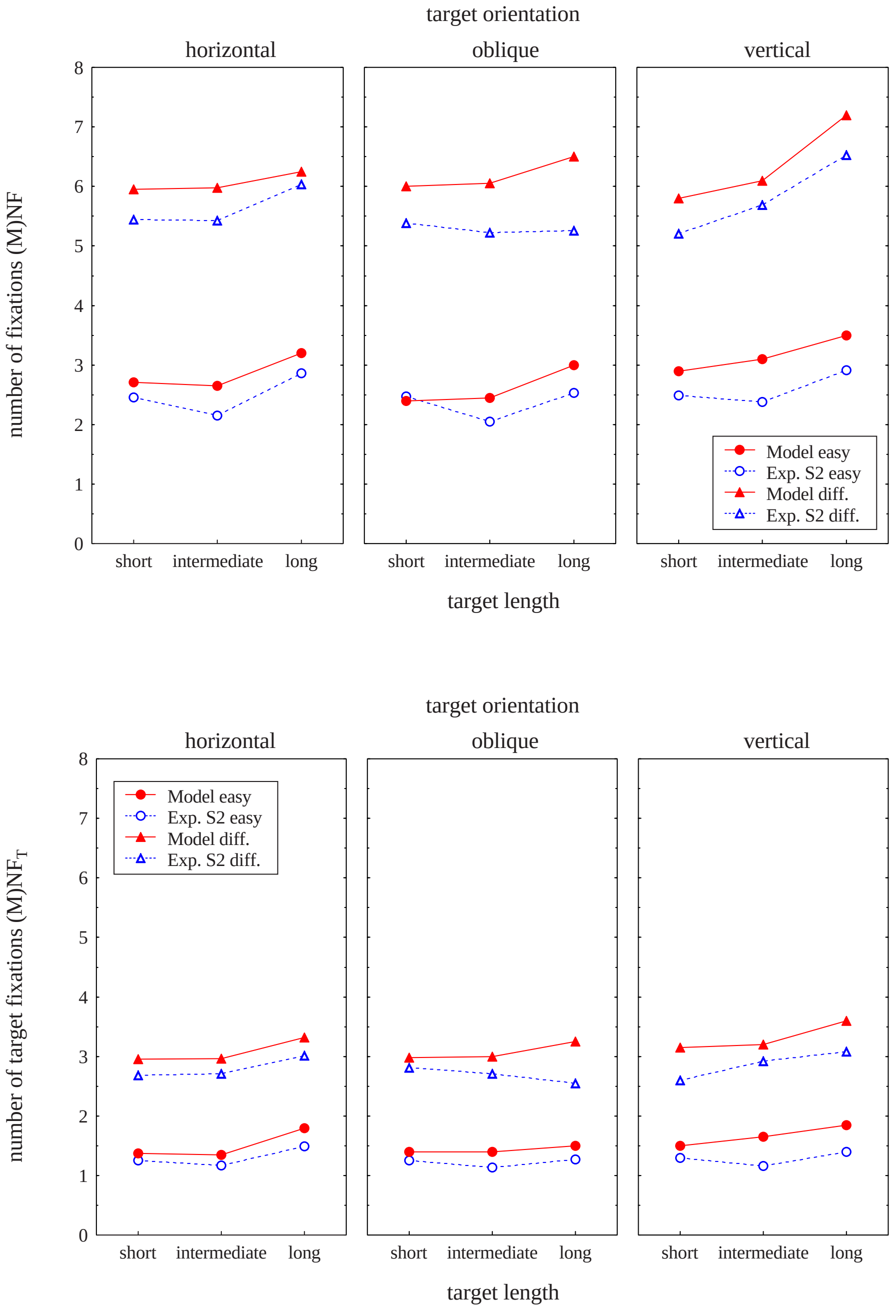


Figure 12.6: Comparison of the empirical (blue dotted) and simulated (red solid) numbers of fixations as a function of target line segment length and orientation when the discrimination task is easy (circles) and difficult (triangles). Top: Overall numbers of fixations NF vs. MNF. Bottom: Target numbers of fixations NF_T vs. MNF_T.

apart and might thus require intermittent fixations more often when attention shifts from one to the other. The same is true when the length of line segments is short.

In general, Figures 12.6 and 12.7 show that the model produces slightly more fixations than subjects do in Experiment S2, an effect consistent with the prolonged reaction times MRT found previously. Although this effect is again not significant so that the model performance can be considered adequate with respect to this (first) eye-movement parameter, it suggests that some of the model parameters, for example those that determine the den-

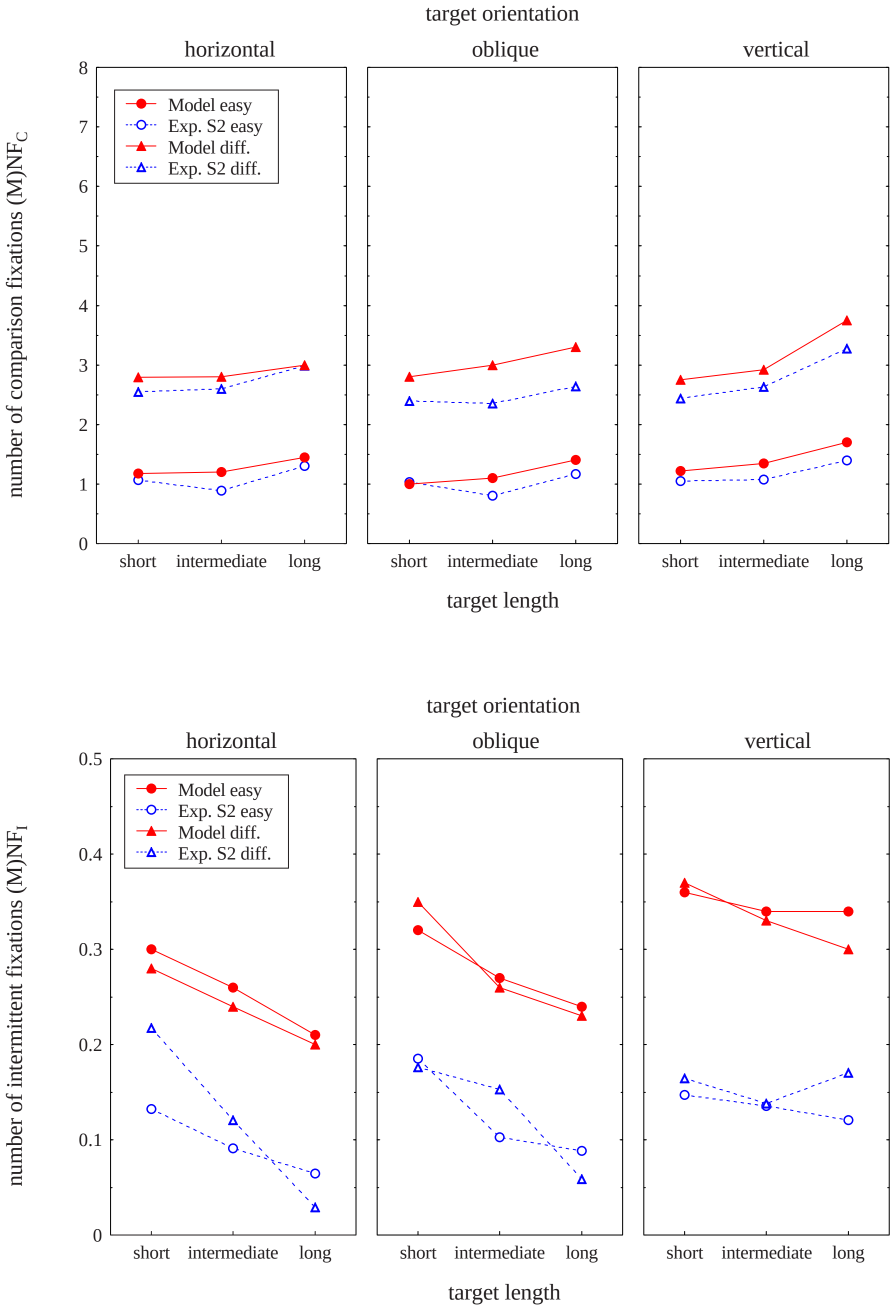


Figure 12.7: Comparison of the empirical (blue dotted) and simulated (red solid) numbers of fixations as a function of target line segment length and orientation when the discrimination task is easy (circles) and difficult (triangles). Top: Comparison numbers of fixations NF$_C$ vs. MNF$_C$. Bottom: Intermediate numbers of fixations NF$_I$ vs. MNF$_I$. (N.B.: Different vertical scale used in the bottom chart.)

sity distribution functions and their approximations or the "noise models", might still require some optimisation. In addition, the model reproduces the numbers of intermittent fixations MNF$_I$ on a higher overall level than given by the empirical data. Although the absolute difference appears negligible in relation to (M)NF$_T$ and (M)NF$_C$, this might also account for some of the empirical–model differences. Nevertheless, the resemblance of the modelled numbers of fixations to the empirical ones is quite good. Furthermore, when viewed in relation to the convincing model reproduction of the discrimination correctness

DC, it indicates that the correlation between conventional and eye-movement variables as found in Experiment S2 could apparently be transferred to the model. Even after only investigating the model performance of one of the eye-movement parameters, the chosen model implementation might indeed be capable of reproducing the subjects' discrimination performance while applying adequate visual processing strategies. Having obtained this promising, but preliminary, finding we can now hope to find similar correspondences between the other (empirical and model) variables as well.

Model Fixation Duration MFD

With the model implementing the simulation of the fixation durations as the approximation of the distribution of the empirical FDs, a reliable reproduction accuracy must be expected. This is in particular true as individual distributions for the various factor combinations of discrimination difficulty, target line segment length and orientation were considered. However, as the Monte Carlo simulation will attempt to model parameterised distributions that assume Gaussian distributions – which, in reality, they are not exactly – some deviation from the subject data would not come as a surprise. In this comparison of model and empirical data as well as in the subsequent ones for the remaining eye-movement parameters, the most relevant categories, namely the overall values and the ones for the two hemifields, will be considered.

Indeed, the four-factorial analyses of variance do not reveal any significant main or interaction effects that involve the factor experiment. For the comparison of the overall fixation duration (M)FD the analysis yields ($F(1;66) = 3.82; p = 0.450$) for the main effect of the factor experiment. FD_T and MFD_T ($F(1;66) = 2.45; p = 0.512$) and FD_C and MFD_C ($F(1;66) = 3.97; p = 0.401$) do not differ significantly between the model

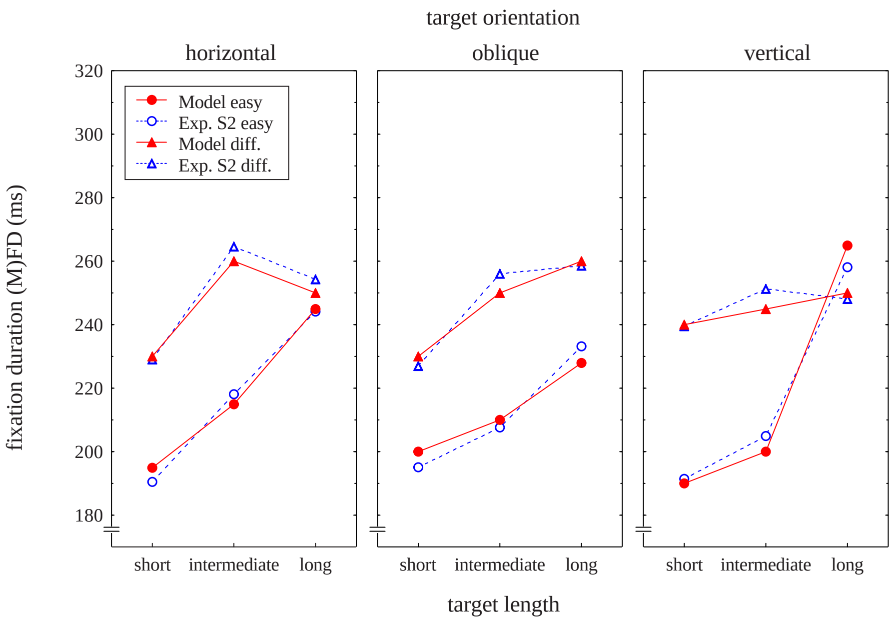


Figure 12.8: Comparison of the empirical and simulated overall fixation durations FD (blue dotted) and MFD (red solid) for the target line segment lengths (short, intermediate, long) and orientations (horizontal, oblique, vertical)when the discrimination task is easy (circles) and difficult (triangles).

and experimental data sets either. This is also illustrated in Figures 12.8 and 12.9 where all model means for all factor combinations closely resemble those of the empirical data from Experiment S2. Only rather small deviations are visible in some cases. Furthermore, these deviations appear to be random rather than systematic, indicating that the assumed Gaussian density distribution was appropriate for the probabilistic model approach chosen to simulate the fixation durations – otherwise, i.e. in case of systematically either lower or higher MFDs than FDs, it would have been more appropriate to employ skewed distributions such as a χ^2 or a Gamma function in order to adequately describe the empirical distributions of FDs.

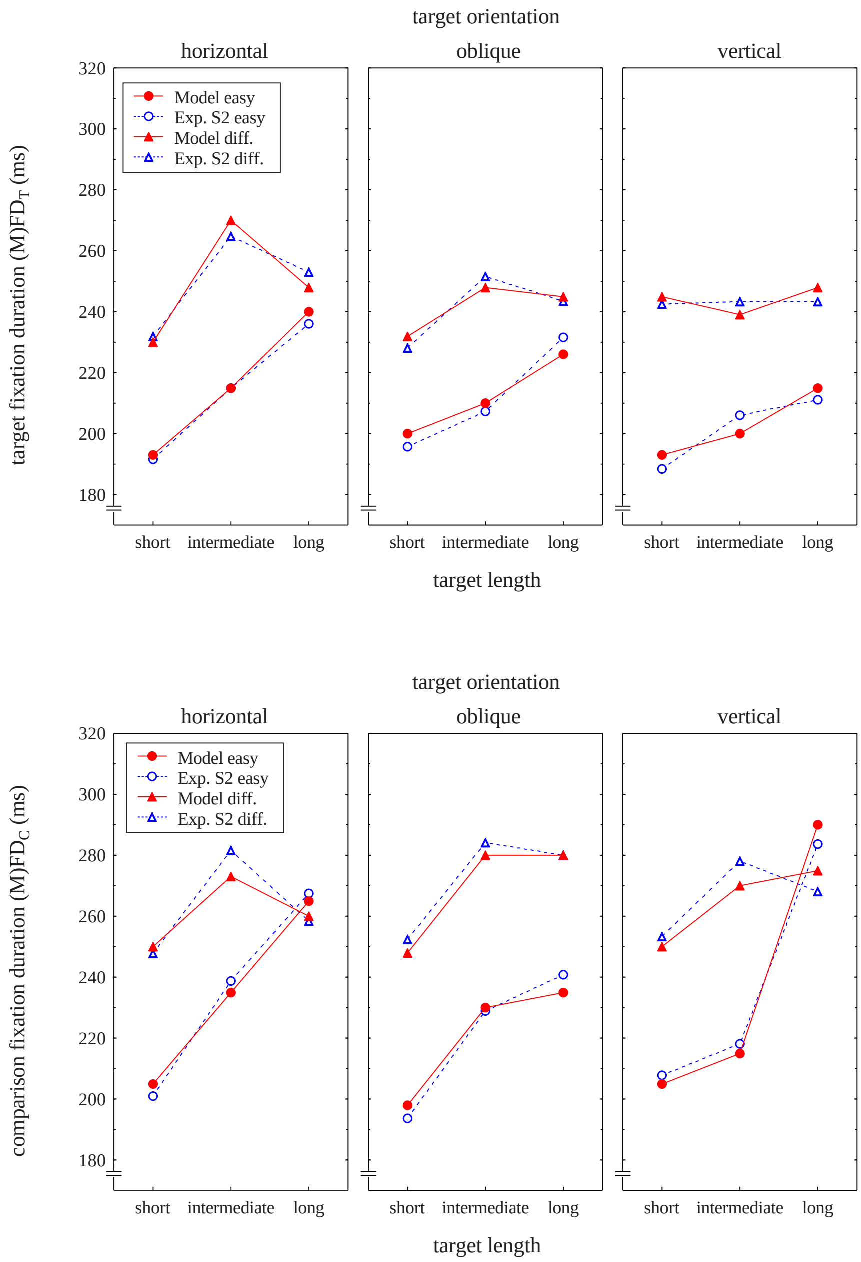


Figure 12.9: Comparison of the empirical (blue dotted) and simulated (red solid) fixation durations as a function of target line segment length and orientation when the discrimination task is easy (circles) and difficult (triangles). Top: Target fixation duration FD_T vs. MFD_T. Bottom: Comparison fixation duration FD_C vs. MFD_C.

Model Number of Saccades between Hemifields MSB

As Figure 12.10 shows qualitatively, the model also quite accurately reproduces the numbers of saccades between hemifields. The modelled shifts of attention between the stimulus constituents significantly vary between the easy and difficult discrimination conditions in the same way as they do in the empirical data. The main effect of the factor experiment does not reach significance level ($F(1;66) = 0.75; p = 0.390$). The characteristics of the "global" variable MSB not only indicate that the model successfully simulates the global processes of either holistic (few shifts of attention) or analytic (several shifts of attention) visual processing. Furthermore, it can be assumed that this is only so because the model also shows similar "behaviour" to that of subjects on the local processing level: The specific strategies the model applies in order to locally assess the line segments' length, i.e. local peripheral length assessment in case of an easy discrimination task and foveal visual measurement via saccades in case of a difficult discrimination task, apparently yield length assessments that are accurate enough to solve the discrimination task after few shifts of attention (holistic mode) or require several re-assessments, update and validation of existing length representations.

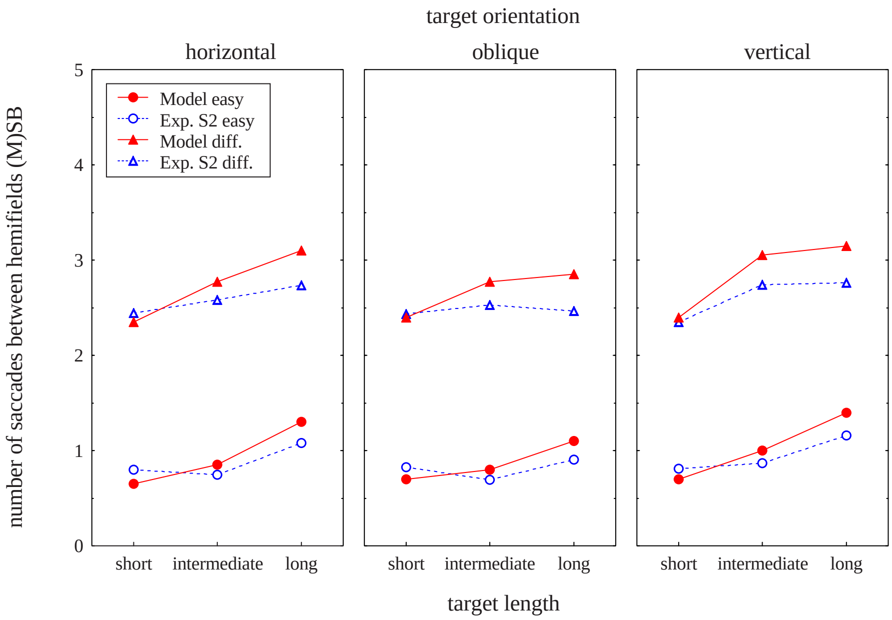


Figure 12.10: Comparison of the empirical and simulated numbers of saccades between stimulus hemifields SB (blue dotted) and MSB (red solid) for the target line segment lengths (short, intermediate, long) and orientations (horizontal, oblique, vertical) when the discrimination task is easy (circles) and difficult (triangles).

Although a good overall correspondence is noted between model and empirical data, a significant four-way interaction is found ($F(4;264) = 1.23; p = 0.041$). The post-hoc comparison of means using the Newman-Keuls test demonstrates that the empirical and the model data differ in the difficult discrimination condition when long oblique ($R_{crit} = 0.67; p = 0.045$) or long vertical line segments ($R_{crit} = 0.64; p = 0.038$) have to be assessed. The model algorithm then requires more shifts of attention between hemifields than subjects. This finding for long, not co-linearly oriented line segments during analytic assessment can probably be understood when considering that this combination certainly represents the most complex condition for the comparison and discrimination task. On the local processing level the model will quite often have to integrate data from more than just two successive fixations. These extra computations have been modelled to decrease the assessment accuracy and take extra time so that more re-assessment of stimuli in particular for this combination may be required. Conceivably, this assessment modelling on the local visual processing level in analytic mode slightly "over-deteriorates" the length representations. However, the reproduction of the empirical data is still achieved quite convincingly. Even for the factor combinations where significant differences are found, these only amount to approximately 0.4 saccades.

Model Number of Successive Fixations within the same Hemifield MFW

Finally, it must be verified if the model reproduces the empirical data for the local eye-movement parameters. When the simulated numbers of successive fixations within the same hemifield and saccade lengths do not differ significantly from those obtained from the subjects' eye-movement recordings, the chosen implementation apparently succeeds in adequately modelling the foveal visual measurement of line segment length via saccades. The analysis of variance does not yield a significant main effect for the influence of the factor experiment on the aggregated number of successive fixations within the same hemifield (M)FW ($F(1;66) = 1.82; p = 0.451$). Furthermore, no significant influence of the factor experiment can be found on the separate numbers of successive fixations within the target hemifield (M)FW$_T$ ($F(1;66) = 1.02; p = 0.381$) or within the comparison hemifield (M)FW$_C$ ($F(1;66) = 1.25; p = 0.254$).

The comparison of means (see Figures 12.11 and 12.12) shows again that the model produces slightly more successive fixations within the same hemifield than subjects do. This general upward shift of model data which was already noticed in some of the other parameters may thus to some extent be attributed to the model more often executing three successive fixations to measure a line segment length than subjects do in analytic mode. This is in particular so when the two line segments are not co-linearly oriented. However, whereas subjects significantly more often execute such fixations when the target is vertical, the model also quite often generates an extra fixation when targets are oblique. Furthermore, it appears that MFW increases for not co-linearly oriented line segments of medium length. The resulting measuring saccades should most likely be alternating ones in an attempt to validate and improve the representation accuracy of the first visual length measurement.

Such an overestimation of the numbers of successive fixations, in particular for oblique and/or intermediate targets – compared to the empirical ones – are in fact most noticable in MFW$_C$. This can be understood when considering that the model implementation takes into account the representation of the previously generated target length. For longer, oblique (or vertical) targets this representation is usually less accurate than the compari-

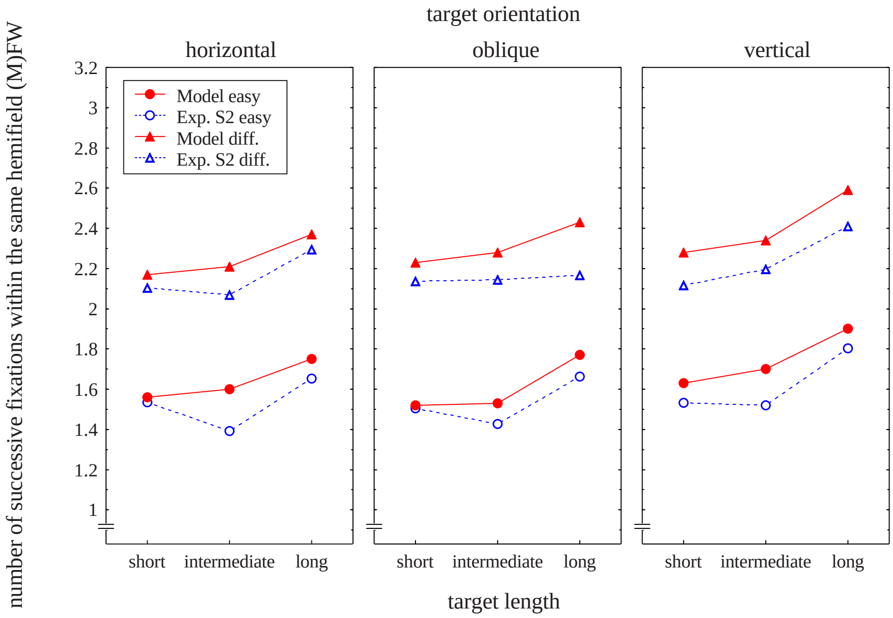
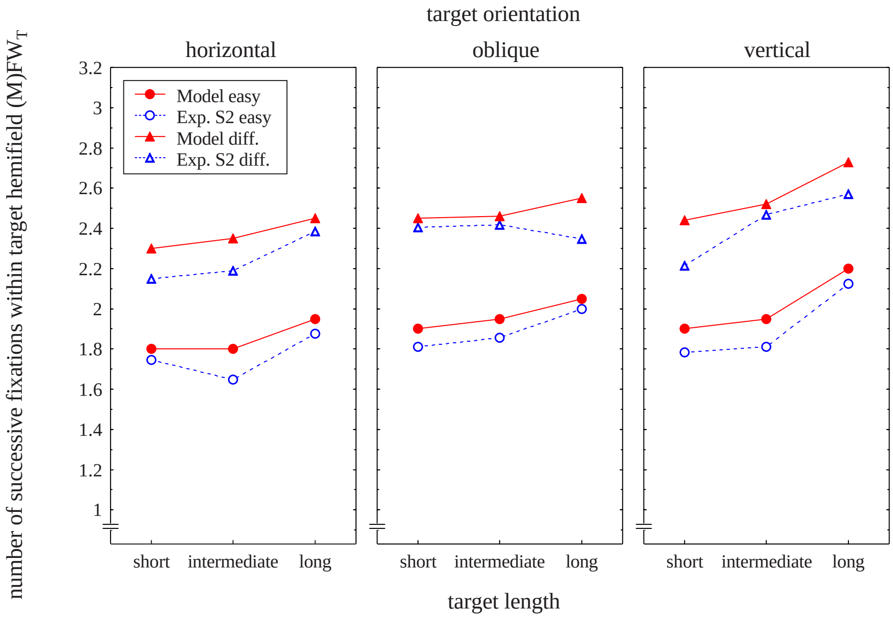


Figure 12.11: Comparison of the empirical and simulated numbers of successive fixations within the same hemifield FW (blue dotted) and MFW (red solid) for the target line segment lengths (short, intermediate, long) and orientations (horizontal, oblique, vertical) when the discrimination task is easy (circles) and difficult (triangles).

son representation. While subjects, after visually measuring the comparison line segment and so far failing to solve the discrimination task yet, probably realise that mainly the inaccurate target representation has to be improved and thus shift their attention back to that stimulus constituent, the model does not. Instead, as currently attending to the comparison stimulus anyway, the algorithm first updates that length representation using an alternating saccade before shifting attention back to the target for reassessment.

The statistical analysis demonstrates that indeed a significant interaction effect exists between the factors experiment, target length and orientation on (M)FW$_C$ ($F(4; 264) = 5.67; p = 0.043$). The subsequent post-hoc comparison of means further yields significant differences between the model and the empirical data only for oblique intermediate ($R_{crit} = 0.22; p = 0.031$), oblique long ($R_{crit} = 0.27; p = 0.038$) and vertical intermediate ($R_{crit} = 0.26; p = 0.047$) targets when the discrimination is difficult. In particular the seemingly different (M)FW$_C$ values for horizontal and oblique intermediate targets in the easy discrimination condition (see Figure 12.12, bottom) do not contribute to this effect. The charts suggest that the algorithm slightly more often switches over to analytic mode in case of an easy discrimination task in general, and, more often so, for those specific factor combinations. Although the effect is not significant it can be speculated that the implementation of the local peripheral length assessment does not yield sufficiently accurate length representations for the more complex stimulus configurations. The then applied analytic visual processing would lead to the increase of MFWs. The statistical analysis does not yield any further significant interaction effects.

In general, the model reproduction can again be considered quite successful with respect to (M)FW. Only some deviations from the empirical data emerge. As the above



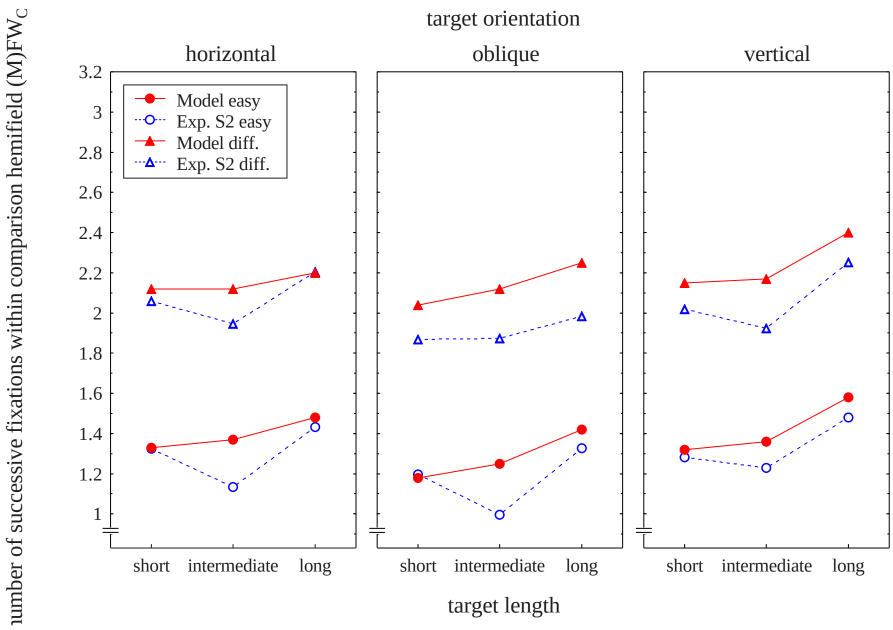


Figure 12.12: Comparison of the empirical (blue dotted) and simulated (red solid) numbers of successive fixations within the same hemifield as a function of target line segment length and orientation when the discrimination task is easy (circles) and difficult (triangles). Top: Number of successive fixations within the target hemifield FW_T vs. MFW_T. Bottom: Number of successive fixations within the comparison hemifield FW_C vs. MFW_C.

discussion shows, these become explicable when taking into account the model implementation and hint at some model deficits. Nevertheless, the general good (simulation/reproduction) performance suggests that the assumed local visual strategies and their differences depending on the discrimination difficulty have been adequately represented by the model algorithm so far.

Model Saccade Length MSL

Finally, the evaluation of the model results with regard to saccade length has to be accomplished. Model and empirical data will be compared for the saccade lengths between hemifields (SL_b vs. MSL_b) and for the saccade lengths within each hemifield (SL_T vs. MSL_T and SL_C vs. MSL_C). Furthermore, the ratio of the modelled within-hemifield saccade lengths

$$MDL = (MSL_C - MSL_T)/MSL_T \tag{12.17}$$

can be interpreted as the (relative) length deviation between the measurement of the target and comparison line segment lengths, i.e. as describing target length over- or underestimation. MDL can thus be compared to the relative length deviation DL measured in Experiment S1. This allows us to validate if the suggested model approach also reproduces the effects induced by the horizontal-vertical illusion – presuming that such visual illusory effects can at least partially be attributed to oculomotor processes.

The four-factorial analysis of variance does not yield a significant main effect of the factor experiment on the saccade length between hemifields $(M)SL_b$ ($F(1;66) = 0.56; p = 0.625$). Furthermore, none of the possible two-, three- or four-way interaction effects involving the factor experiment reach significance level either. Figure 12.13 supports the high correlation between the model and the empirical data. However, a comparison of means and the closer inspection of Figure 12.13 reveal that now MSL_b is longer when the discrimination task is easy than when it is difficult. A separate analysis of variance shows that the effect of discrimination difficulty on MSL_b is a significant one ($F(1;33) = 1.56; p = 0.001$). This finding is inverse to the observations in the empirical data, when SL_b was found to be significantly shorter for easy than for difficult discriminations ($F(1;33) = 1.79; p < 0.001$,

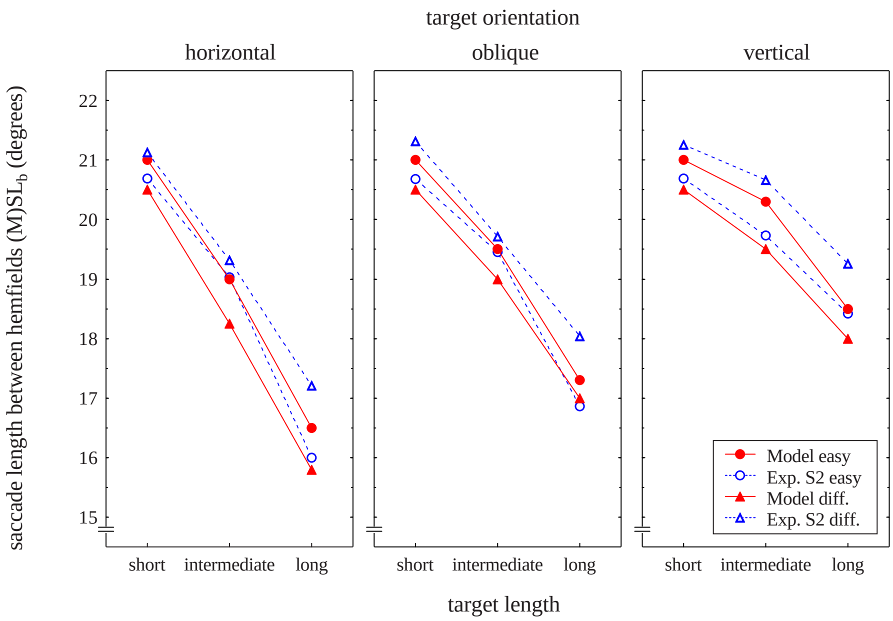


Figure 12.13: Comparison of the empirical and simulated saccade lengths between hemifields SL_b (blue dotted) and MSL_b (red solid) for the target line segment lengths (short, intermediate, long) and orientations (horizontal, oblique, vertical) when the discrimination task is easy (circles) and difficult (triangles).

see Section 11.3). This may be due to the model algorithm often generating inter-stimulus saccades that start at the mid-point of one line segment and aim at the mid-point of the other when in holistic mode. In contrast, usually the innermost end point of the line segment in the other stimulus hemifield is aimed at when the model executes shifts of attention in analytic mode. With those inter-stimulus saccades often also starting at the innermost end point, MSL_b should be shorter in analytic than in holistic model mode.

As found for most other eye-movement parameters before, the model quite accurately

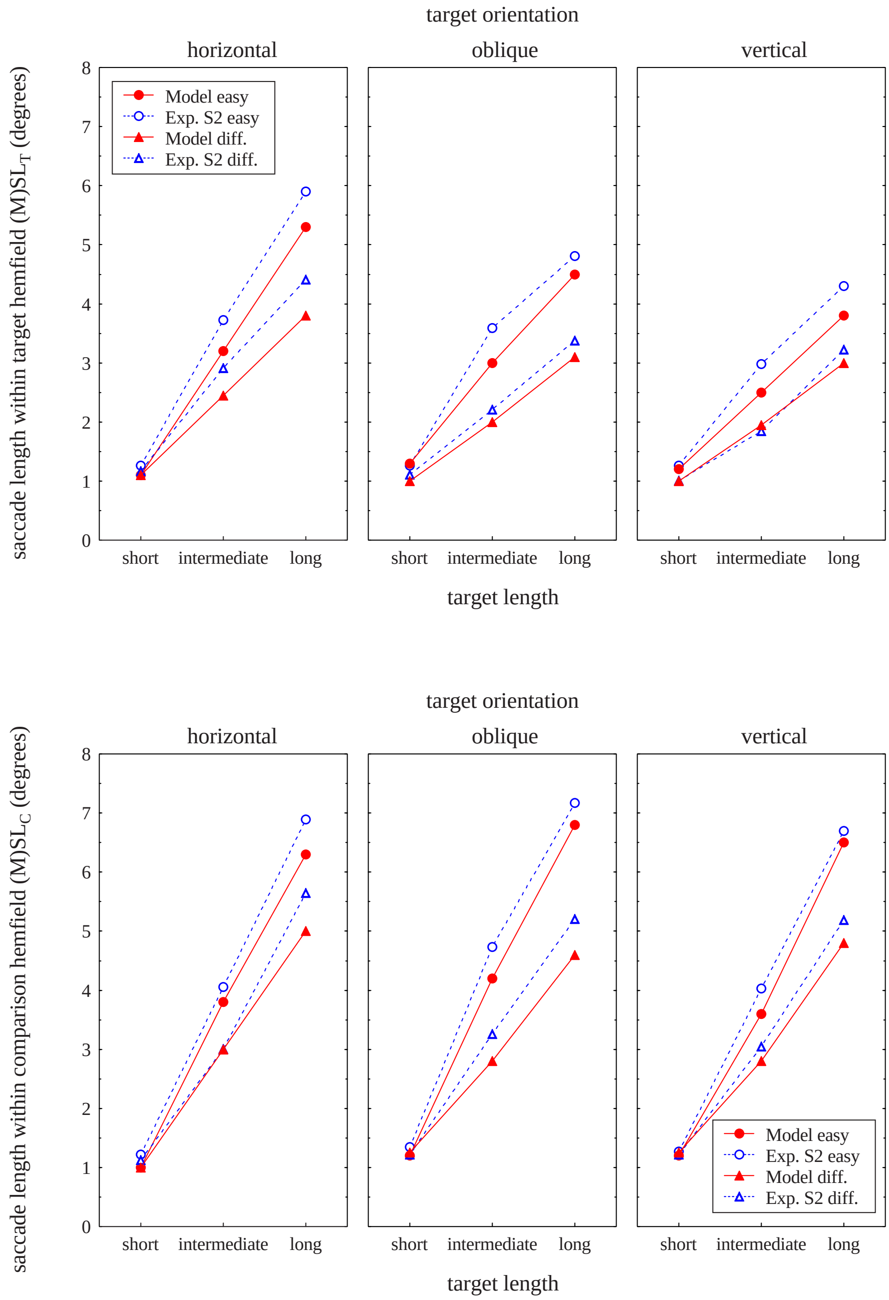


Figure 12.14: Comparison of the empirical (blue dotted) and simulated (red solid) saccade length within the same hemifield as a function of target line segment length and orientation when the discrimination task is easy (circles) and difficult (triangles). Top: Saccade length within the target hemifield SL_T vs. MSL_T. Bottom: Saccade length within the comparison hemifield SL_C vs. MSL_C.

reproduces the saccade lengths within each hemifield. Neither a significant main effect of the factor experiment on (M)SL_T ($F(1;66) = 2.45; p = 0.421$) or (M)$SL_C$ ($F(1;66) = 2.00; p = 0.355$) nor any interactions with the factors discrimination difficulty, target line segment length and/or orientation can be found. Although not significant, the lengths of the model saccades in particular within the target hemifield MSL_T appear to be slightly shorter than the empirical values. This could again support the earlier observations that the model may actually execute two "in-line" measuring saccades more often, leading to a decrease of the respective saccade lengths. Furthermore, the model might also generate slightly more corrective saccades, possibly due to deficits in the model determination of saccade landing points. Subjects might achieve this task more accurately and thus require less corrective saccades. Compared to the measuring saccades, these are usually quite short and can thus be thought to influence MSL even when only few are executed.

Figure 12.14 illustrates the again close correspondence between the two data sets for (M)SL_T (top) and (M)SL_C (bottom). Interestingly here, the curves for holistic and analytic processing are not reversed as found for (M)SL_b. This is in line with the specifications of the model algorithm for foveal visual measurement of line segment lengths: When the model applies measuring saccades for the foveal assessment of line segment lengths although the discrimination task is easy, these will always measure half the length of a line segment. Two successive saccades "in-line" (to measure the same fraction of the line segment, but consequently yielding saccade lengths of only one quarter of the length of the line segment) will not be executed as is the case for some of the saccadic measurement when the discrimination task is difficult. Furthermore, corrective saccades are generally not executed when in analytic mode for easy discriminations – whereas the model would have executed them for similar situations when the discrimination is difficult. Thus, on average, the saccade lengths within each hemifield MSL_T and MSL_C are shorter when

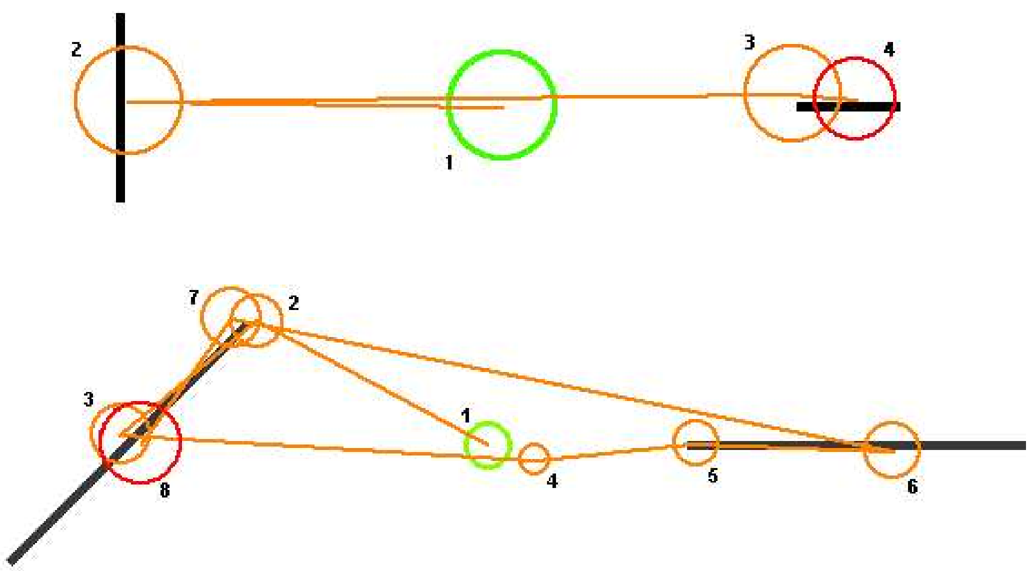


Figure 12.15: Model gaze trajectories in the easy (top) and difficult (bottom) discrimination conditions.

the discrimination is easy than when it is difficult – similar to the observations in the subjects' data SL_T and SL_C.

This yet again clearly indicates that the assumed (local) visual processes in both holistic and analytic mode were adequately represented in the model. In fact, the good reproduction of eye-movement parameters can be understood to have enabled the accurate reproductions of the more "conventional" parameters. The local visual processes, either local peripheral length assessment or foveal visual measurement via saccades, could apparently be parameterised in the model implementation in an adequate manner. The quantitative analysis is further supported by qualitative data. *Gaze trajectories* that were generated by the model (Figure 12.15) and those that subjects produced (see Figures 3.9 and/or 11.18) closely resemble each other. Finally, the application of visual strategies implemented according to empirical specification yields appropriate length representations so that the subsequent modelling of the comparison and representation update processes also generates proportions of discrimination correctness MDC that very closely resemble those of subjects.

This only leaves us to verify if there also exists a correlation between the ratios of the modelled saccade lengths within each hemifield (see Equation 12.17), yielding MDL, and the relative length deviations DL as measured in Experiment S1. At first sight, Figure 12.16 does not seem to present very promising results in favour of such a positive correlation: Neither are the absolute values of DL and MDL of the same magnitude nor is MDL able to reproduce the effect of DL to decrease for longer target length. Instead MDL drastically increases from short through intermediate to long targets (Figure 12.16, left). However, two rather important correspondences between DL and MDL can be found: First, MDL can be understood as producing an *overestimation* of the target length which is in line with DL. Second, this overestimation increases when the two line segments are not co-linearly oriented. Furthermore, the model even reproduces the strong increase in DL from horizontal to oblique and the less pronounced increase from oblique to vertical (Figure 12.16, right) – to be precise, MDL does not increase from oblique to vertical, but remains at the same level.

With respect to the horizontal-vertical illusion, orientation effects can certainly be

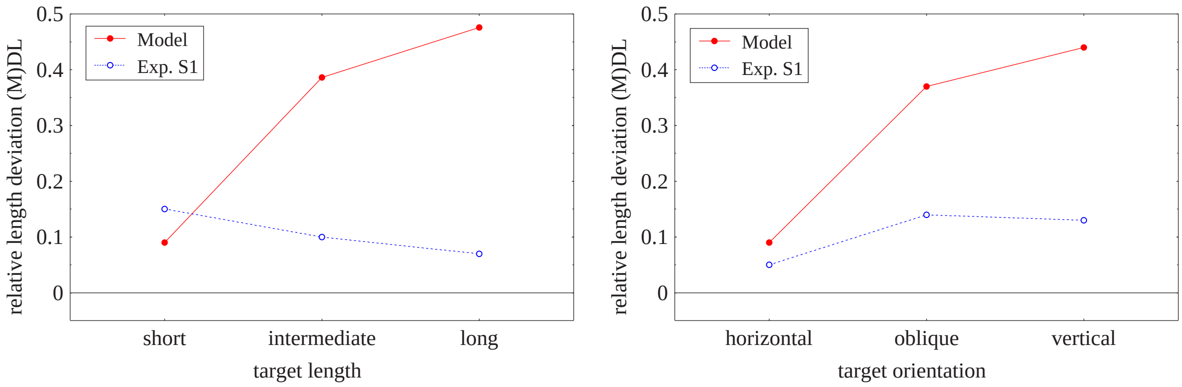


Figure 12.16: Comparison of the empirical (blue dotted) and simulated (red solid) length deviations DL and MDL as a function of target line segment length (left) or orientation (right).

considered as more relevant than length effects. The model, using the ratios of measuring saccades to represent deviations in perceived lengths, quite correctly reproduces these orientation effects and, more specifically, the overestimation of the length of oblique targets. Although the extent of the illusory effect is certainly on a different magnitude scale, this finding appears to present some support for at least partially attributing this illusory effect to low-level sensorimotor processes. Apparently, the oculomotor system has a severe deficit executing accurate measuring saccades when the lengths of line segments that are not co-linearly oriented are foveally assessed. Mental length representations based on these inaccurate measurements will probably not be very accurate either. However, as the model is not capable reproducing all effects observed in the empirical data and only simulates the illusory effect on a different magnitude scale, oculomotor processes alone cannot explain all aspects of the horizontal-vertical illusion.

The following section summarises the fundamental results of Chapters 9–12.

12.5 Summary and Conclusions

After the contributions of peripheral perception processes to the overall understanding of line segment assessment had been established earlier, the investigation then moved on to studying line segment perception in a more complex scenario. The focus here has been on similarity effects in line segment length perception during simultaneous comparison tasks. This scenario appeared to be particularly promising for the investigation of different visual strategies that subjects apply in order to solve discrimination tasks – *holistic visual processing for easy discriminations vs. analytic visual scene analysis for difficult discriminations.* The comprehension of the perceptual mechanisms and the underlying cognitive processing steps should be greatly facilitated by the analysis of eye movements which manifest the pursued visual strategies. The chosen scenario also appeared promising with a view to modelling the observed empirical visual behaviour. With saccade planning (not only) for such visual strategies being largely guided by peripheral information processing, an attempt should be made to integrate the previous findings into a comprehensive explanatory approach. Based thereupon, it should further be possible to develop a computational model that adequately describes line segment perception and comparison while taking into account components of the eccentricity model of Chapter 8.

The first experiment in this series, Experiment S1, already yields great support for some of the hypothesised fundamental mechanisms that are applied to assess line segment length within the present comparison scenario. Furthermore, it becomes clear that without the analysis of eye movements, these mechanisms and visual processing strategies would have been difficult – if not impossible – to establish. The discussion of results for example shows that *foveal "visual measurement"* of line segments appears to be the central element of length assessment, generally characterised by two successive fixations on the respective line segment. The saccade length between the two fixations closely coincides with the overall length of the respective line segment when it is short or, when longer, only covers a specific fraction of the line segment. Additional information on the size of the fraction in relation to the overall length must be *memorised* along with the *mental representation* of the saccade length for the subsequent comparison. This requires the incorporation of peripherally perceived information on the outermost end point of the line segment in question and suggests that line segments must be *decomposed* in simultaneous comparison tasks as well.

Eye movements further indicate that after the visual measurement of one of the two stimulus constituents, *attention shifts* to the other line segment. The comparison stimulus is analogously assessed, i.e. visually measured, and the correspondingly generated representation mentally compared with the previously memorised one. If the two representations are not found to match in length, the comparison is adjusted and the mental comparison executed again with the updated comparison representation. This procedure can be re-iterated several times until the two representations of the target and comparison line segments are found to match in length. Fixation data also suggests that sometimes intermittent saccades to the target line segment occur (single fixations only), probably to "refresh" the initially memorised target representation – in particular when numerous adjustment steps are necessary to match the comparison length.

The investigation of eye movements in Experiment S1 also yields valuable information on the extent of the stimuli-induced *horizontal-vertical illusion* and provides new approaches to assist its understanding: Taking the visual measurement strategy into account, saccade lengths indicate that mental representations of lengths larger than the physical lengths of target line segments are stored and referred to for comparison and matching. This may cause the typical overestimation of oblique and vertical line segments induced by the illusion. The finding suggests that the illusory effects may at least partially be attributed to deficits during low level, *oculomotor* processing. Here, the dynamic adjustment procedure applied in Experiment S1 proves indispensable. The stimulus-induced horizontal-vertical illusion could only be quantified using this procedure.

Even more importantly, the dynamic procedure yields the essential data to determine easy and difficult discrimination conditions in the following Experiment S2. However, Experiment S2 is not only required to investigate the corresponding holistic and analytic visual strategies. Comparing results from Experiments S1 and S2 suggest that, for example, fixation times FD and the distribution of fixations in the comparison hemifield are influenced by the *dynamic procedure* of Experiment S1. It apparently distracts subjects from the "pure" length perception task and makes it difficult to reliably attribute specific effects solely to the dynamic adjustment process or to the actual line segment assessment task. The static scenario in Experiment S2 should eliminate the "side-"effects induced by the dynamic adjustment procedure in Experiment S1 and thus allow us to explore length perception principles in even greater detail.

The fundamental conclusion that can be drawn from Experiment S2 is that indeed *two distinct visual processing strategies* can be established, depending on the discrimination difficulty. Furthermore, the discussion demonstrates that the initial hypothesis appropriately classifies these strategies as *"holistic"* and *"analytic"*. In accordance with the initial definition of holistic, subjects only coarsely visually scan line segments that exhibit a low length similarity. When length similarity is high which makes the discrimination difficult, a detailed foveal analysis of the line segments is conducted to accurately assess and represent their lengths for a subsequent mental comparison.

When the discrimination task is easy, the discussion of the results of Experiment S2 reveals that the *holistic strategy is applied locally rather than globally*. Even in the easy discrimination condition subjects usually fixate each stimulus constituent (at least) once. They locally peripherally assess the length of the respective line segment. A single fixation is found to be sufficient in almost all cases to successfully accomplish the discrimination task. As further findings strongly indicate that the line segments' end points are of particular relevance for length assessment, this very sparse fixation pattern only allows for the coarse perception of the line segment lengths and constitutes a process that is entirely peripheral. In some cases, however, when the target and the (always horizontally oriented) comparison line segments are not co-linearly oriented, a detailed foveal analysis of the target is conducted. This is in particular so when the assessment is further complicated because the line segments are so long that they cannot be perceived peripherally that easily. Switching to analytic visual mode is thought to yield a more accurate target length representation, mentally rotated to match the comparison orientation, and subsequently compared to the comparison representation. The comparison length is perceived peripherally so that this process can still be classified as locally holistic. In all cases, the generated representations are accurate enough to correctly discriminate the lengths in an instant. Only a single shift of attention between the two stimulus constituents is sufficient before subjects make their decision.

When the discrimination task is difficult, an analytic visual processing strategy is pursued throughout. The discussion supports *local, foveal "visual measurement"* as a fundamental principle in assessing line segment lengths within both the target and the comparison hemifield. This visual measurement principle is generally characterised by two successive fixations within the same hemifield. Even more than in the previous Experiment S1, these fixations are now located "on" the target or the comparison stimulus. The saccade length between the two fixations closely coincides with the overall length of the respective line segment when it is short or, when longer, only covers a specific, usually the *innermost, fraction* of the line segment. In particular the generation of mental representations of obviously complex target line segments – such as those that are long and not co-linearly oriented to the comparison – often requires step-by-step visual analysis of the target where three successive fixations are executed. In a considerable number of these cases, gaze "alternates" between two designated locations on the line segment and can be thought to augment the length representation or to improve the representation accuracy. Additional information on the size of the fraction in relation to the overall length is also stored along with the mental representation of the saccade lengths for the subsequent comparison. This is probably achieved by incorporating peripherally perceived information on the outermost end point of the line segment in question. Data yields that apparently half of the overall physical length of the respective line segment is visually measured, constituting a *"multiplication" factor of two*.

When data perceived by multiple successive in-line fixations must be integrated, the addition of several saccade lengths obviously demands greater cognitive and memory "effort" in order to store, maintain and compare the various representations. Such representations are apparently not ideal as it becomes increasingly difficult to integrate multiple data. Furthermore, data itself is more complex. Rather than representing half the length of a line segment, *"odd" fractions* must now be processed. The discrimination correctness considerably decreases in such cases. In analogy to the findings in Experiment S1, eye movements further indicate that after the visual measuring of one of the two stimulus constituents and the generation of a corresponding mental representation, attention directly shifts to the other line segment. The comparison stimulus is analogously assessed, i.e. visually measured, and the correspondingly generated representation mentally compared with the previously memorised one. If the two representations are not found to yield a significant difference in perceived length, the comparison procedure is repeated and the mental comparison is executed again with the updated representation. In contrast to the easy discrimination condition, these *global shifts of attention* and the subsequent procedure are re-iterated several times when the discrimination is difficult in order to increase the accuracy of the representations – until the length discrimination task can be solved.

The findings render the *decomposition* of line segments essential in both processing modes. The assessment of line segment length apparently requires the assessment of end point locations. In holistic mode length assessment is then accomplished by *fusing* peripherally perceived end point positions to "compute" line segment length. The end point *component(s)* yield important landmark locations for saccade planning and foveal visual measurement in analytic mode. This supports the validity of the initially formulated decomposition hypothesis also in free gaze simultaneous comparison scenarios.

Taking the empirical findings into account, a comprehensive computational model, integrating components of the previous eccentricity model, is implemented. The model is a formalised description of the procedure subjects pursue when they accomplish a simultaneous length comparison task. This is accomplished by parameterising the proposed perception mechanisms so that an algorithmic implementation reproduces the empirical data. After the model pre-attentively "decides" whether to switch to either holistic or analytic mode, based on a global peripheral assessment of the two line segments' lengths, the algorithm simulates saccade planning which resembles that followed by subjects in Experiment S2. The characteristics of the scan path both on the global level, describing the visual inter-stimulus processing, and on the local level, describing the intra-stimulus processing, are taken into account by the model. This is accomplished depending on the discrimination difficulty: Local peripheral length assessment is paired with sparse shifts of attention between stimulus hemifields in holistic mode and foveal visual measurement via saccades is paired with repeated shifts of attention in analytic mode. The eccentricity model that is based on the decomposition hypothesis could rather conveniently be integrated into the implementation of both strategies. It either yields the peripheral length assessments as such in holistic mode or, in both holistic and analytic mode, generates saccade landing points.

The chosen model implementation successfully represents the visual length assessment strategies as applied by subjects in the simultaneous comparison tasks of Experiment S2. It not only achieves a convincing reproduction of the discrimination accuracy, but furthermore does so by applying visual strategies similar to those subjects use. This is strongly supported by a model data set of eye-movement parameters that very closely resembles that obtained in Experiment S2. Both the statistical comparison of these two data sets and the quantitative illustrations of means for almost all independent variables do not yield significant differences. Model-generated gaze trajectories close resemble those of subjects. Furthermore the model implementation, using the length ratios of measuring saccades to represent deviations in perceived lengths as found in Experiment S1, quite correctly reproduces the orientation effect of line segments on perceived length as characteristic for the horizontal-vertical illusion. The length of oblique line segments is overestimated when compared with horizontal ones. It appears that these illusory effects may at least to some extent be attributed to deficits of the oculomotor system when visually measuring line segment lengths.

In summary, Chapters 9–12 have created a rather comprehensive “image” of the visual perception processes and their interaction that determine the underlying strategies during line segment length assessment. In particular the analyses of eye-movement parameters proved essential in this respect. They support the hypothesised holistic and analytic strategies that subjects pursue. These could adequately be represented in a comprehensive computational model, successfully integrating components of the eccentricity model that was developed earlier.

Chapter 13

Conclusions and Outlook

This chapter again summarises the fundamental findings of the present thesis. A great variety of aspects that influence the visual perception of location, orientation and length in different visual comparison scenarios have been investigated and successfully formalised in computational model simulations. Furthermore, an outlook on future research is provided. It is clear that not all aspects could have been considered so far. Some findings also put new questions into view. It thus appears promising, for example, to transfer the identified processing mechanisms to other types of stimuli. This leaves room for future studies, some of which are currently underway and already provide some preliminary results.

13.1 Summary and Conclusions

In principle, the present investigations explored the different processing steps of the cognitive structure which determines visual comparison tasks: *Assessment, memorisation, comparison/matching*. More specifically, the visual mechanisms that guide *line segment perception in sequential and simultaneous visual comparison* scenarios were analysed. Eye movements in particular facilitated the identification of these perception mechanisms and thus allowed to understand how the different cognitive processing steps were accomplished. After initially exploring assumed mechanisms that govern such tasks in isolation, the individual findings could subsequently be integrated to yield a comprehensive, formalised description of the whole process. This description was finally implemented as a computational model. The close resemblance between empirical and simulated data supports the conclusion that the proposed explanatory approaches are reasonable and indeed correctly reflect the cognitive structure of such visual comparison tasks. Unfortunately however, even then there is no final "evidence" that the assumed perception mechanisms are really deployed in the specified manner, i.e. that they are *psychologically adequate*.

The influence of *peripheral vision* as one of the fundamental contributing factors to the assessment of line segments in general was formulated in a *decomposition hypothesis*. The sequence of the Experiments E0–E2 reflected the "decomposition" of complex processes into simpler ones: It should be possible to infer line segment orientation or length from location assessment, assuming that end point information is essential for the assessment of such line segment attributes. More specifically, the assessment of a line segment can be formalised as the localisation of line segment end points and the computation of their distance to yield line segment length. In analogy, the computation of the spatial relation of end points yields line segment orientation.

The first experiment, Experiment E0, consequently investigated the accuracy of location assessment in peripheral vision. Results suggest that the assessment of position is governed by two distinct processes. One is responsible for the assessment of the *direction* where a target marker is situated, a process that obviously works quite accurately and more or less independent of the level of eccentricity of the target. The second process determines the *distance* between fixation point and target. This process yields less accurate judgements as the radial position of the target is significantly *underestimated*. Furthermore, this process is eccentricity-dependent and shows deteriorating assessment accuracy for the radial target position with increasing peripheral viewing. On aggregate, the combination of these two processes yields positional judgements that are dominated by the distance component and results in a perceived position of the target marker that is *shifted towards* the fixation point, but shows very little directional divergence.

In order to validate the decomposition hypothesis, the assessment of the length and orientation of peripherally viewed line segments were investigated in Experiments E1 and E2. The "reference" data obtained in these experiments allowed for the testing of the existence of correlations between the assessment error of peripherally perceived lengths or orientations of line segments and the mislocation of marker positions, depending on eccentricity.

Findings of Experiments E1 and E2 yielded support for the decomposition hypothesis. Based on the observations regarding the "distance" and "direction" components of location assessment, the *overestimation* of the length of peripherally perceived line segments could be explained: When memorising a peripherally perceived line segment, subjects develop a mental model of a line segment of approximately the correct physical length, but *shifted towards the fixation point*. Due to the principle of size/length constancy this mental "shift" of the line segment towards the observer leads to an elongation of the line segment when its mental model is recalled for comparison. The deteriorating accuracy of the assessment of line segment orientation with increasing peripheral presentation could also be explained with reference to the observations in Experiment E0: Due to the greater variance along the radial rather than the tangential axis in location assessment, a considerable variation in orientation assessment must be expected – and could indeed be observed in Experiment E2.

The development of explanations for the observations made in Experiments E1 and E2 that are based on mechanisms which were found to describe the marker mislocation in Experiment E0 strongly *supports the decomposition hypothesis*. Furthermore, the strong links found between the assessment accuracies for location and those for line segment length and orientation encouraged an "integrated" model based on the findings of Experiment E0. An accordingly implemented computer simulation successfully reproduced the empirical data. It yielded line segment length as the distance between the peripherally assessed locations of the line segment end points and line segment orientation as the relative position of the peripherally assessed locations of the line segment end points. Taking the findings of both length and orientation modelling into account, it appears that the chosen approach is indeed *suitable* to adequately reproduce the manifold aspects involved in the peripheral perception of line segment lengths and – with some restrictions – of line segment orientation as well. The model's convincing replication performance *further supports the decomposition hypothesis* and gives rise to the assumption that we correctly identified the perception mechanisms involved in the assessment of line segments, namely the essential contribution of line segment end point information. Furthermore, we successfully implemented these mechanisms in the simulation algorithms.

The eccentricity Experiments E0–E2 yielded a variety of novel insights into visual peripheral processing – which must definitely be rendered quite interesting in its own respect. Viewed within the greater context of the present thesis, the experiments even more so provided data that could be integrated into a comprehensive model describing line segment assessment in a more complex scenario. This was realised in Experiments S1 and S2 which focussed on *similarity effects in line segment length perception during simultaneous comparison tasks*. This scenario appeared to be particularly promising for the investigation of different visual strategies that subjects apply in order to solve *discrimination* tasks – *holistic* peripheral visual processing when the discrimination is easy or *analytic* foveal scene analysis when the discrimination is difficult. In the chosen free gaze scenario, the identification and comprehension of the underlying perceptual mechanisms, again viewed with respect to the underlying cognitive structure of assessment–memorisation–comparison, should be greatly facilitated by the analysis of eye movements which manifest the pursued visual strategies.

Indeed, the analysis of eye movements proved essential in establishing the characteristic visual processing strategies. The fundamental results showed that *foveal "visual measurement"* of line segments appears to be one of the central mechanisms in length assessment. It is generally characterised by two successive fixations on the respective line segment, constituting a "measuring saccade". The saccade length between the two fixations closely coincided with the overall length of the respective line segment when it was short or, when longer, only covered a specific *fraction* of the line segment. Additional information on the size of the fraction in relation to the overall length must apparently be stored along with the *mental representation of the saccade length* for the subsequent comparison, requiring the incorporation of peripherally perceived information on the end point locations of the line segment.

Eye movements further indicated that after the visual measurement of one of the two stimulus constituents *attention shifted* to the other line segment. The comparison stimulus was analogously assessed, i.e. visually measured, and the correspondingly generated representation mentally compared with the previously memorised one. If, given the *dynamic adjustment* comparison task of Experiment S1, the two representations did not match in length, the comparison was adjusted and the mental comparison executed again with the updated comparison representation. Fixation data also suggested that the update can efficiently be achieved by *"refreshing"* the initially memorised representation using single fixations rather than re-iterating measuring saccades. This requires the incorporation of peripherally perceived information on the end points of the line segment and suggests that line segments must be *decomposed* in simultaneous comparison tasks as well.

The analysis of eye movements in Experiment S1 also suggests that the *horizontal-vertical illusion* effects may be attributed to deficits during low level, *oculomotor* processing: The lengths of measuring saccades indicate that mental representations of lengths larger than the physical lengths of target line segments are stored and referred to for comparison and matching which then causes the typical overestimation of oblique and vertical line segments.

The *static* scenario in Experiment S2 then eliminated the "side-"effects induced by the dynamic adjustment procedure in Experiment S1. Depending on the *discrimination difficulty*, i.e. the *length similarity* of two simultaneously presented line segments, the initially hypothesised distinct visual processing strategies could be established. It was indeed appropriate to classify these strategies as *"holistic"* and *"analytic"*. In short, subjects only *coarsely* visually scanned line segments in easy discrimination tasks whereas a detailed foveal analysis of the line segments was conducted to accurately assess and represent their lengths for a subsequent mental comparison in difficult discrimination tasks.

More specifically, when the discrimination task was *easy*, the holistic strategy applied was *locally holistic* rather than globally: Subjects usually locally peripherally assessed the line segment length of each stimulus constituent using a *single* fixation. This suggests an entirely peripheral process where, according to the *decomposition* hypothesis, again the end points of the line segment provide the relevant location information for the subsequent distance computation which then generates the length representation. When the easy discrimination task was more complex because the presented stimuli were long and not co-linearly oriented, subjects often *switched from holistic to analytic* processing mode. However, only the target stimulus was foveally measured, the horizontally oriented comparison mostly locally holistic assessed. Only a *single shift of attention* between the two stimulus constituents was sufficient for subjects to make a highly correct decision – Which of the two line segments is the longer one? – in the easy discrimination condition.

An *entirely analytic* visual processing strategy characterised *difficult* discrimination tasks: *Local, foveal "visual measurement"* constituted the fundamental mechanism to assess line segment lengths within *both* the target and the comparison hemifields. The saccade length between two successive fixations "along" a line segment closely coincided with the *entire* length of short line segments. In contrast, measuring saccades only covered a specific, usually the *innermost, half* of longer line segment. In order to obtain an appropriate mental representation of line segment length it is thus required to *memorise a "multiplication" factor of two* along with the *length of the measuring saccade*. The representation accuracy may be improved when "alternating" measuring saccades between two designated locations on the line segment "enforce" the length representation.

More complex representations made up from three successive in-line fixations were also found, often when assessing long and not co-linearly oriented stimulus configurations. The integration of multiple saccade lengths and multiplication factors is apparently not ideal; the discrimination correctness considerably decreased in such cases.

Mental length representations were subsequentially generated of both the target and the comparison stimuli, "visually linked" by *shifts of attention* between the two line segments. If the *comparison* of the *memorised* length representation with the length of the currently inspected line segment did not produce a significant length difference, the assessment, representation and comparison steps were re-iterated in order to increase the accuracy of the representation(s) – until the length discrimination task could be solved.

All mechanisms observed, local peripheral assessment in holistic mode and saccadic measurement of line segments (or fractions thereof) render the *decomposition* of line segments essential. The assessment of line segment length apparently requires the assessment of end point locations. In holistic mode length assessment is then accomplished by *fusing* peripherally perceived end point positions to "compute" line segment length. The end point *component(s)* yield important landmark locations for saccade planning and foveal visual measurement in analytic mode. The current findings thus support the validity of the initially formulated decomposition hypothesis also in free gaze simultaneous comparison scenarios.

Based on the empirical findings and the proposed perception mechanisms and visual strategies, a *comprehensive computational model, integrating components of the previous eccentricity model*, was implemented. The model is a formalised description of the procedure subjects pursue when they accomplish a simultaneous length comparison task. This was accomplished by parameterising the proposed perception mechanisms so that an algorithmic implementation can reproduce the empirical data. First, the model preattentively decides whether to switch to holistic or analytic mode, based on a global peripheral assessment of the two line segment lengths. The algorithm then simulates saccade planning which resembles that followed by subjects in Experiment S2 and largely depends on discrimination difficulty: Local peripheral length assessment paired with sparse shifts of attention between stimulus hemifields in holistic mode and foveal visual measurement via saccades paired with repeated shifts of attention in analytic mode.

The eccentricity model could rather conveniently be integrated into the implementation of both strategies and represents the decomposition and "fusion" mechanisms. It either yields the peripheral length assessments as such in holistic mode or, in both holistic and analytic mode, generates saccade landing points. In order to appropriately account for memory aspects that influence the mental mapping of the length representation, the model also incorporates a memory component. Implemented as a decay function mainly taking gaze duration into account, it causes length representation accuracy to deteriorate over time. This makes the discrimination task more prone to error, in particular for more complex, multi-fixation assessments of line segments. The memory component also contributes to modelling the illusory effects induced by the horizontal-vertical illusion: With the assessment of an oblique or vertical target line segment requiring more fixations, the subsequent data integration takes longer so that the target length representation is subject to stronger decay than the comparison representation.

The chosen model implementation quite successfully represented the visual length assessment strategies. It did not only achieve a convincing reproduction of the discrimination accuracy as found in Experiment S2, but furthermore did so by applying similar visual strategies as subjects do. This is strongly supported by a model data set of eye-movement parameters that very closely resembles the one that was obtained in Experiment S2. Model-generated gaze trajectories also closely resemble those of subjects. Finally, the model implementation quite correctly reproduces the orientation effect of line segments on perceived length as characteristic for the horizontal-vertical illusion: The modelled length of oblique line segments is overestimated when compared to horizontal line segments.

In summary, this thesis set out to create a comprehensive image of the visual perception processes that characterise the underlying strategies of line segment length assessment in comparison tasks. In particular, the analysis of eye-movement parameters proved essential in this respect. They yielded support for the *hypothesised holistic and analytic visual strategies* that subjects pursued. The respective visual processing and perception mechanisms could adequately be represented in a comprehensive computational model, successfully integrating the eccentricity model that is based on the *decomposition hypothesis*.

13.2 Outlook

Reasonable explanations could be proposed for most of the empirical findings and subsequently be formalised to yield a convincing model representation. However, several observations put new questions into view. These obviously require further investigation and alternative explanatory approaches. Whereas length assessment under both peripheral and foveal viewing conditions could adequately be represented in respective computational models, these models present significant deficits with respect to *orientation* assessment. This could indicate that the location of end points is possibly not one of the essential mechanisms behind orientation assessment. Rather than the determination of the relative position of a line segment's end points, other mechanisms may yield its orientation. Indeed, the existence of explicit *orientation-sensitive receptive fields* in the visual cortex might provide quite accurate orientation data already. Rather than information present at the end points of a line segment, it would be more likely then that the central region of a line segment is of particular interest. The findings of additional experiments carried out in the Bielefeld eye-tracking group (Ströker, 2002) are in line with this hypothesis. When only the end points of a line segment were presented (see Figure 13.1, left), the accuracy of peripheral orientation assessment deteriorated – compared to that for the assessment of line segments as used in Experiment E2. If end points were indeed the key components of a line segment for orientation assessment, their presence "undistracted" by the actual line segment should have rather improved the orientation assessment accuracy. Instead, the opposite happened, indicating that the line segment itself is essential for orientation processing, possibly as "input" for the receptive fields.

It can be further speculated that the visual system is actually capable of compensating for the lack of receptive field input by applying an alternative orientation assessment strategy, namely the end point dependent strategy proposed in the eccentricity model. However, it obviously causes severe problems when neither of the two strategies can be pursued alone, as was the case in another experiment where Ströker (2002) used line segment fractions (see Figure 13.1, right). Here the accuracy of peripheral orientation assessment was again significantly worse than when only end points were shown. It appears that two *concurrent* visual processing strategies collide: Whereas end points are quite difficult to determine as the line segment now yields four (two per fraction) instead of two of them, the receptive field might encounter further difficulties due to the lack of the central fraction of the line segment. Thus neither of the two possible strategies in isolation yields accurate orientation assessment and, when combined, the aggregated result might yet again be worse.

Figure 13.1: Stimuli used in Ströker's (2002) experiments. Left: Line segment end points. Right: Line segment fragments.

The findings of the present investigation also inspire further research. After the investigation of mechanisms that guide the visual perception of characteristic attributes of one-dimensional objects, various options are available. The current investigations could, for example, be extended to *higher dimensional stimuli*, studying size and volume perception. Here, an attempt could be made to transfer – and possibly adapt – the existing processing mechanisms for one-dimensional stimuli to account for size and/or volume perception. Alternatively, empirical findings might indicate that the development of new mechanisms is required. For simple, symmetric geometrical shapes, it indeed appears realistic that visual measurement of contours yields size information and should thus lead to equivalent mechanisms as found in the assessment of line segments. This should be true in particular for those figures with explicit junctions, i.e. corners, that may attract visual attention – compared to "round" figures where visual "landmark" points can be determined less reliably. Here, visual measurement of radii (for circles or ellipses) might be feasible to obtain size assessments or to be able to discriminate different shapes.

Taking the third dimension into consideration, the situation would certainly be more complicated again. Whereas similar principles may again apply as for the assessment of one- and two-dimensional stimuli, it would be particularly interesting to see how "real" three-dimensional figures are assessed. In comparison with the less-dimensional stimuli, vergence eye movements must now be taken into account and observer–object distances and varying perspectives must be considered as well. This then leads to a whole new field of research, namely that of *mental representations of three-dimensional objects*. This poses not only the question of how to compare their various attributes, but also how the mental representations are initially generated – prior to the actual comparison.

Studies by Koesling, Ritter, Carbone and Sichelschmidt (unpublished) already at-

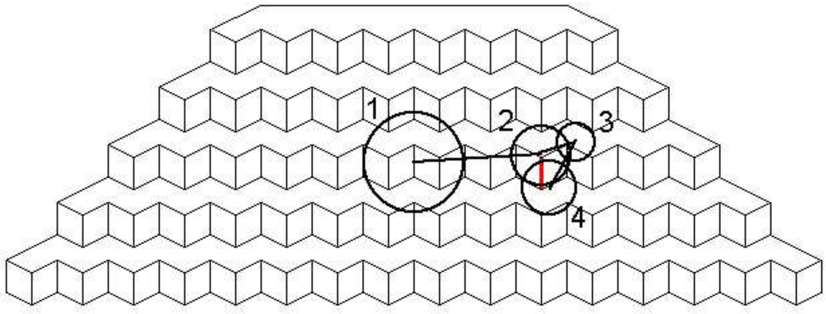


Figure 13.2: Sample stimulus used to investigate the generation of mental representations of three-dimensional geometrical objects. Overlaid is a typical gaze trajectory subjects produced when they had to decide whether the red line segment was convex- or concave-oriented.

tempted to investigate which aspects determine the generation of mental representations of three-dimensional scenes, employing rather complex object configurations (see Figure 13.2). Results indicate that the generation of such mental geometrical representations is guided by the integration of *foveally* perceived *local object attributes* ("Is this edge convex or concave?") and *peripherally* perceived *global scene information* ("Are the steps receding or protruding?"). Figure 13.2 shows a sample stimulus overlaid with a typical gaze trajectory.

These findings were initially regarded contradictory to the authors' hypothesis for the perception of such complex scenarios: They assumed that mental representations were generated here in synchrony with a detailed foveal fixation pattern, visually analysing the figure – an idea based on connectionist approaches for the interpretation of line drawings (Guzman, 1968; Winston, 1992). Following a relaxation algorithm (Waltz, 1975), junctions and edges can be labelled (see Figure 13.3) so that attributes of specific junctions or edges, for example convex or concave, can later be retrieved. When the labelling can be completed successfully, the consistency of the whole figure can be determined. Correspondingly, this also enables the algorithm to identify "impossible figures" when labelling cannot be accomplished consistently. However, the implementation of such an approach to simulate corresponding gaze trajectories using a relaxation algorithm did not yield

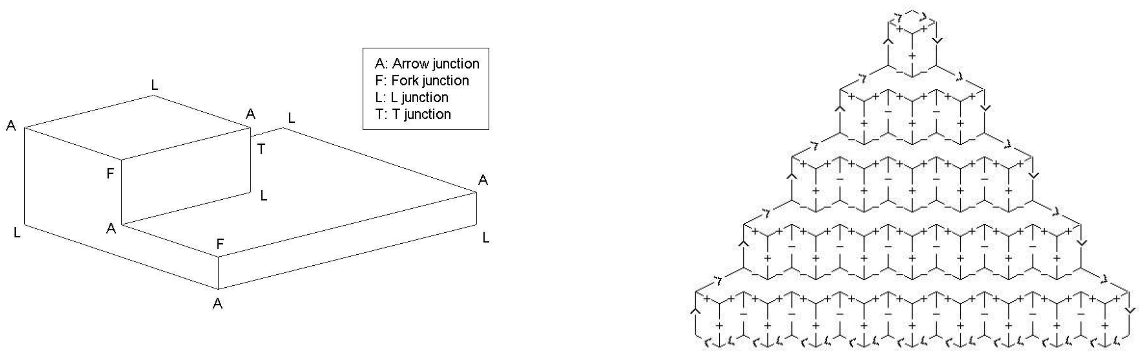


Figure 13.3: Classification and labelling of junctions (left) and edges (right) according to Waltz's (1975) algorithm. The algorithm usually "contracts" (i.e. relaxes from outer to inner picture elements) and labels edges based on the preceding junction classification.

close correspondence with the empirical results. On the other hand, the foveal scanning of the relevant local information paired with global peripheral figure assessment appears, in principle, not too different from the assessment mechanism found in the Experiments S1 and S2. This finally gives rise to the assumption that even for the assessment of characteristic attributes of three-dimensional stimuli at least some of the identified perception mechanisms apply, in particular when investigated in simplified scenarios as used in Experiment S2.

Moving along the axis of *semantic content*, the current investigations could be extended to stimuli that allow for a *conceptual interpretation*. Although previous studies using Mooney Faces (see Section 2.1) did not render an eye-movement approach very successful, the investigation of eye movements may be more promising when more "convenient" stimuli are chosen and presented in a less "crowded" scenario. It was apparently difficult to identify the faces within the Mooney stimuli. The identification was further complicated as stimuli pictures contained several Mooney Faces. In addition, in some experiments, Mooney Faces were "morphed", i.e. the contours of adjacent faces were merged, so that face recognition was almost impossible – and thus not accomplished. The visual scanning strategy was obviously guided by geometrical factors rather than by conceptual considerations. Instead, stimuli should be chosen for future studies that can be *recognised easily* and *interpreted unambiguously* and only consist of a *single* stimulus constituent. The "easy" recognition should at least allow for the *categorisation* of the stimulus, i.e. "face" and should be accomplished *pre-attentively* so that recognition and comparison do not interfere. Eye-movement studies might then indeed be suitable to explore the different steps of the cognitive structure of such comparisons. It could, for example, be hypothesised that *decomposition* strategies can again be identified. However, "components" might be different and be chosen in accordance with *conceptual* rather than in accordance with *geometrical* consideration. This *conceptual strategy* is presumably induced by the specific *task* and the stimulus *category*: The decision which of two cars is the faster one will most likely be determined by other components than the decision which of two faces looks nicer. The first task might require a *functional, objective* visual analysis of the relevant components of a car whereas the second rather suggests an *emotion-guided, subjective* decomposition of typical features of a face.

In summary, the above-mentioned aspects should be considered in new series of studies that are apparently closely related to the present investigations. These present investigations have successfully contributed to a better understanding of the cognitive structure of visual comparison tasks when characteristic object attributes such as location, line segment length or orientation have to be assessed. Empirical eye-movement investigations allowed us to propose fundamental processing mechanisms. Line segments, for example, can be assessed either *holistically* or *analytically* depending on the *discrimination difficulty*. Furthermore, the assessment apparently requires the *decomposition* of the stimulus: Length assessment may be accomplished by the assessment of locations of line segment end points. This location information is subsequently *fused* to yield the distance between the end points and thus the line segment length. The length is *mentally represented* and *memorised* as the distance between one end point that is foveally viewed and the second end point that is *peripherally* perceived. Alternatively, line segment length can be represented as the length of a *measuring saccade* along the line segment or a fraction thereof. If the mental representations are not sufficiently accurate to solve a given comparison task – Which of two line segments is the longer one? – assessment and mental mapping are re-iterated.

The proposed processing mechanisms could be successfully integrated in a comprehensive, formalised model which was implemented as a computer simulation. The simulation reproduced the empirical observations in a convincing manner. This yields further support for the involvement of the proposed mechanisms in the assessment of line segment attributes in comparison scenarios.

Object assessment in visual comparison scenarios is now open to a wide range of new research. Inspired by the present findings, it does not only appear promising to further explore abstract, low-dimensional stimuli. The assessment of *high-dimensional* geometrical figures and objects with a *high semantic content* must also be considered highly rewarding. Eye movements should again provide valuable insight into the perception processes and the underlying cognitive structure of such complex comparisons. In conclusion, there is no doubt that this field of research still provides a large number of aspects for exploration in the future.

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