The temporal and spatial dynamics of Visual Attention for object recognition and visuomotor behavior: Studies on pre- and transsaccadic selection

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CUMULATIVE DISSERTATION

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Summary

Humans perceive their visual environment by means of two distinct orienting mechanisms. Eye movements overtly orient the retinas high resolution fovea towards relevant information. Additionally, processing resources are covertly allocated across space and time, in order to preferentially process relevant visual information without moving the eyes. The latter is referred to as Visual Attention. This cumulative dissertation comprises three studies which address the temporal and spatial dynamics of Visual Attention and its role in object recognition, respectively eye-movement control. Moreover, it is studied how Visual information is selected and maintained across successive eye movements. The present synopsis first of all introduces theoretical work that is relevant to the overall research questions. Finally, the discussion of this synopsis relates the results of the three studies. The following topics were addressed in the three studies, respectively:

The Attentional Blink is a well-known experimental paradigm for studying limitations in temporal Visual Attention. Typically in this paradigm two targets require pattern recognition. Here it is studied whether localizing a peripheral target for a visuomotor task interferes with subsequent pattern recognition in an Attentional Blink-like fashion. The results indicate that limitation in the allocation of Visual Attention over time may also be found when targets belong to different functional subdomains for object recognition and visuomotor behavior

The second study seeks out a transsaccadic coupling of Visual Attention and eye movements. There is ample evidence that before a saccade is executed, Visual Atttention is allocated towards the saccades' goal location. This study investigated whether visual information is processed preferentially at the saccades goal location after an eye movement. It could be shown that despite deviations of the saccade from its goal location Visual Attention is allocated within the fovea to the intended goal location of the saccade. Thus indicating that object recognition and saccade target selection rely on a common selection mechanism across a saccade.

In the third study it is investigated in how far the Attentional Blink affects processing across successive fixations. While this interference phenomenon has been typically investigated within a fixation, research on viewing behavior in natural task settings suggests that visual information often has to be processed across successive fixations. Therefore the third study tested whether the Attentional Blink can be found when targets are separated by an eye movement. It was found that discrimination of a target in one fixation impairs identification of a second target in a trailing fixation, i.e. a transsacdic Attentional Blink

Together the results of the three studies indicate that object recognition as well as visuomotor behavior rely on common processing resources. These are distributed across time and space by means of a Visual Attention mechanism. Moreover, processing resources are not only shared among visual input within a fixation, but competition also depends on selection and maintenance of information from the previous fixation. Overall this highlights that visual perception relies on an intricate interplay of overt and covert orienting mechanisms.

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1. *Introduction*

Everyday tasks such as reading or car driving require processing of visual information. Humans move their eyes several times per second to potentially informative locations in order to pick up visual information that serves the current behavioral goals. Besides this overt orienting behavior, over the past decades experimental cognitive psychology has identified an additional form of selecting visual information. The latter does not result in an observable behavior but it occurs covertly. Experimentally it can be inferred by participants' ability to detect, discriminate or identify visual information. It is referred to as selective Visual Attention.

Research on both orienting mechanisms has benefited greatly from advances in technology. More specifically, computer controlled stimuli presentation has made sophisticated research on temporal and spatial characteristics of attention possible. The widespread introduction of eye-tracking technology allowed researches to gain insight into mechanisms of eye-movement control. Together with these technological advances, the notion grew within cognitive psychology that for understanding visual perception mechanistically it is especially relevant to study the relation of both orienting systems.

The current dissertation addresses the temporal and spatial dynamics of the covert orienting mechanism and its role in object recognition, respectively eye-movement control. Moreover, all three studies highlight the close link between covert and overt orienting systems by addressing pre- and transsaccadic mechanisms of selection.

In the following, a theoretical background will be presented on three main topics. First, an introduction into eye-movements will be given, with an emphasis on a certain kind of eye-movement, that is, saccadic eye-movements. The second part summarizes selected findings and concepts in the field of Visual Attention, relevant to the current work. Finally the third part outlines some research on the link between eye-movements and Visual Attention. Following the theoretical background, the research questions for the three manuscripts will be presented. The empirical part consists of the three manuscripts which are at the core of the current dissertation. The last section, the general discussion, first of all summarizes briefly the finding from the three studies, before discussing their interrelation with respect to the theoretical background presented in the introductory chapter.

1.1. *Eye Movements*

In order to perceive parts of the visual environment the human brain processes signals arriving from the eye's light sensitive retina. The retina shows an inhomogeneous distribution of receptors, i.e. visual resolution decreases from central to peripheral areas of the retina (Hirsch & Curcio, 1989). The retina's central two degrees, the so called fovea, are mainly composed of color sensitive cones, whereas the peripheral retina consists mostly of contrast sensitive rods. Moreover, there is a disproportion of cortical tissue representing central as compared to peripheral retinal information, and, receptive field sizes increase with retinal eccentricity (e.g., Cowey & Rolls, 1974). For these reasons high visual acuity as well as color vision is limited to the fovea. In order to pick up detailed visual information distributed across space, the fovea has to be aligned with potentially informative locations.

In humans this is achieved by means of eye-movements, of which several types can de differentiated: the vestibulo-occulor reflex keeps objects of interest at the center of gaze by compensating head movements; smooth pursuit eye-movements follow moving objects; vergence movements allow both eyes to move in opposing direction to an object at a different distance to the observer (cf., Gilchrist, 2011). The current work focuses on saccades, which are fast ballistic movements of both eyes in one direction. Depending on the task, humans produce up to four saccades per second. Due to their high velocity of up to 900° s^{-1} vision is blurred during saccade execution and processing visual information is additionally suppressed for approximately the duration of the movement (for an overview see Matin, 1974). Therefore, humans are unable to perceive visual information during saccades. Consequently, visual information has to be gathered when the eyes are almost stationary, during the so called fixations. The size of a saccade is referred to as its amplitude, i.e. the distance between starting- and endpoint of the saccade in degrees of visual angle. Saccade duration increases approximately linearly with its amplitude. For example a saccade of 6° would have a duration of around 30-40 ms. Saccade latency reflects the time it takes from stimulus presentation until the movement is initiated. Saccade latency shows great variability across individuals, different tasks or types of stimulus presentation (see Hutton, 2008). For example latencies are considerably longer if they are elicited by endogenous information (e.g., an arrow pointing to a location) as compared to exogenous information (an abruptly appearing object; e.g., Walker, Walker, Husain, & Kennard, 2000). A latency of around 200ms may be considered average (Carpenter, 1988). The landing position of a saccade towards a visual target is typically hypometric, that is, their amplitude reaches about 90% of the targets' eccentricity (Becker & Jürgens, 1979).

Saccades are termed prosaccades if they are directed towards a peripheral target and antisaccades when they are directed to the mirrored target location in the opposite hemifield. Delayed saccades are initiated after a goal signal is provided, and memory guided saccades are executed towards a remembered location. These different types of saccade are often used to infer the cognitive mechanisms behind occulomotor control (cf., Hutton, 2008). Research further suggests strong interactions of eye-movements with attention and working memory systems (cf., Theeuwes, Belopolsky, & Olivers, 2009)

1.2. *Visual Attention*

Within Cognitive Psychology and Neuroscience the concept of Attention has attracted a great deal of interest over the last couple of decades. Generally Attention can be seen as a control mechanism that reflects the prioritization of information processing from low to high level cognition (cf., Chun, Golomb, & Turke-Browne, 2011). Relevant information has to be selected over irrelevant information because the brain's processing capacity is limited (Boadbent, 1958; Deutsch & Deutsch, 1963), i.e., not every piece of information available at a given moment in time can be processed.

Visual Attention refers to the mechanism that selects visual information. Already Helmholtz (1896) was able to show that it is possible to keep the center of gaze at one location whilst perceiving visual information at another location. In the classic Posner cueing paradigm (e.g., Posner & Cohen 1984) participants had to detect a stimulus appearing within one of two peripheral boxes. A cue was presented prior to stimulus onset. This could be either a brief brightening of one of the small peripheral boxes (exogenous cue) or an arrow appearing at fixation (endogenous cue) pointing to either of the potential target locations. For both types of cues manual reaction times where faster if the cue pointed the location of the target. Thus, visual attention was covertly allocated to the location that was indicated by the cue. Posner (1980) termed this covert orienting to distinguish it from the actual overt orienting response, i.e. an eye-movement.

Many theories on Visual Attention (e.g., Bundesen, 1990; Wolfe, 1994; Desimone & Duncan, 1995) differentiate between top-down and bottom-up control over selection. On the one hand, selection is top-down controlled when it is driven by the current behavioral goals. It is said to reflect voluntary attentional control (cf., Egeth & Yantis, 1997). On the other hand, bottom-up factors refer to salient physical properties of visual information (e.g., an abrupt onset or a uniquely colored object; e.g., Theeuwes, 1991; Yantis & Jonides, 1990). These can lead to an automatic allocation of Visual Attention. An amalgamation of both factors has been termed attentional priority (e.g., Facteau & Munoz, 2006).

Metaphorically Visual Attention was long conceived as a mental spotlight which moves in a serial fashion from one location to the next (e.g., Posner, Snyder, & Davidson, 1980). There is now evidence that rather than a unitary spotlight, attention is allocated in parallel across the visual field (e.g., Bundesen, Kyllingsbaek, & Larsen, 2003). Nowadays, an important theoretical concept for understanding how processing resources are distributed across space is that of a priority map (Facteau & Munoz, 2006). Activity on these spatio-topically organized maps represents a combination of saliency and task-relevance: The higher the activity at a location on the map, the more likely that the object at that location is selected.

In Bundesen's 'Theory of Visual Attention' (TVA, 1990, see also Bundesen & Habekost, 2008), selection in space is formally described in terms of a race of visual objects for categorization in 'Visual Short Term Memory' (VSTM). The probability for a specific object to be categorized in VSTM is determined by the weight that is assigned to that object. Weights are computed for all objects in the visual field depending on a combination of bottom-up and top-down factors. The theory fares well at capturing effects from a wide range of experimental paradigms (i.e., cueing paradigms, visual search as well as whole and partial report), studying selectivity within spatially distributed visual information.

Generally, the allocation of processing resources across space is considered a central feature of Visual Attention. However, visual information is not only distributed across space but also across time. That is, the visual system has to select relevant visual information before it disappears or is replaced by irrelevant information. Moreover, relevant visual information may be quickly followed by further relevant information. Thus, it is important to study how processing resources are distributed across time.

The Attentional Blink has been a central paradigm for capturing the temporal dynamics of Visual Attention (for an overview see Dux & Marois, 2008). It refers to the finding that accuracy in reporting a second of two targets is diminished for about half a second. In the classical canonical Attentional Blink paradigm (e.g. Raymond, Shapiro, & Arnell, 1992) multiple stimuli are displayed at a central foveal location using rapid serial visual presentation (RSVP, Lawrence , 1971) at a rate of around 10Hz . Participants are typically asked to identify or detect two of these stimuli. These stimuli are thus task relevant and termed targets. The two targets (T1 and T2) can be defined by a certain feature (e.g. size or color, e.g. Raymond, Shapiro, & Arnell, 1992) or category (e.g., alphanumeric class, e.g., Chun & Potter, 1995). The remaining task-irrelevant stimuli are to be ignored by the paticipants, and thus termed distractors. By varying the serial position of T2 relative to T1 (i.e., the lag) it has been found that the probability to detect or identify T2 correctly follows a u-shaped trend across lags. More specifically when T2 follows T1 without intervening distractors (i.e., at lag 1) T2 performance is high. However, with one or more intervening distractors T2 performances is impaired for about 500ms. T2 performance reaches unimpaired performance for longer target-onset asynchronies (TOA). Similar results can be obtained in the related Dwell-Time paradigm (Duncan, Ward, & Shapiro, 1994), in which targets and their respective masks are presented at different peripheral locations. The main Attentional Blink finding (i.e. the second target deficit lasting up to 500 ms) is typically explained as reflecting limitations in attentional resource for T2 while

T1 is being encoded or consolidated into short term memory (e.g., Chun & Potter, 1995; Jolicoeur & Dell'Aqua, 1998, Bowman & Wyble, 2008; Petersen, Kyllingsbaek, & Bundesen, 2012; but see Olivers & Meeter, 2008). More generally, the Attentional Blink could reflect the time that attention needs to be allocated to an object until it has been fully processed (e.g., Desimone & Duncan, 1995; Moore, Egeth, Berglon, & Luck, 1996; Ward, Duncan, & Shapiro, 1996).

The Attentional Blink highlights limitations in selecting visual information for object recognition over time. Within the framework of 'Biased Competition' (Desimone & Duncan, 1995) selection is a result of competition of sensory input for perception and control of visuomotor-behavior. In this sense selectivity may not only be seen as a consequence of attentional capacity limitations in object recognition, but also as a functional consequence of output limitations in motor control (see also Neumann, 1987). The latter refers to selection-for-action, while the former has been termed selection-for perception (Alport, 1987). Hence, Visual Attention is not only an important for object recognition but also for guiding actions such as arm- or eye-movements. Both of these functions are likely to rely on different cognitive computations. On the one hand pattern recognition is necessary for identifying a specific letter and on the other hand goal-directed eye- or arm-movement require localization. To a certain degree these are likely to be performed in different subsystems of the human brain (Ungerleider & Mishkin, 1982). Visual Attention is necessary to resolve competition within both of these functional domains (cf., Desimone & Duncan, 1995). An important question that is being raised by this assumption: to what degree selection-for-perception and selection-for-action rely on the same attentional mechanisms, i.e., do they depend on a common processing resource.

1.3. *Visual Attention and Eye Movements*

A close relation between covert- and overt-selection almost seems self-evident, considering that accurate visual perception can only be achieved by interplay of both orienting mechanisms. Consequently, this matter has attracted a great deal of interest within vision research over past decades (e.g., Klein, 1980; Posner 1980; Posner & Cohen, 1984; Sheppard, Findlay, & Hockey, 1986; Rizzolatti, Riggio, & Sheliga, 1994; Hoffmann & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Deubel & Schneider, 1996; Awh, Armstrong, & Moore, 2006).

Rizzolatti, Riggio, and Sheliga (1994) argued for a causal role of ocular motor programming in the allocation of visual attention. More specifically, they deemed programming and preparation of an eye-movement both necessary and sufficient for the allocation of Visual Attention to a specific location. Attentional facilitation of visual processing without actually executing an eye-movement, as in an endogenous cueing experiment, is accomplished by aborting the eye-movement to the cued location. This strict version of the relation between Visual Attention and eye-movements has been criticized (e.g., Smith & Schenk, 2012)

Deubel and Schneider (1996, see also Schneider & Deubel, 2002) argued for a common attentional mechanism underlying object recognition and saccade target selection. They could show that preparing a saccade to one location actually improves discriminating an object at that location compared to neighboring locations. Additionally, it is not possible to allocate attention to another location than to the goal of the eye-movement. They reasoned that an allocation of Visual Attention to a certain location is necessary for programming an eye-movement to that location. In this sense, selection-for-perception and selection-for – action rely on a common attentional resource (Schneider, 1995).

Results from Baldauf and Deubel (2008) further suggest that Visual Attention can be allocated to the goal locations of a sequence of saccades prior to execution of the first eye-movement. Deubel (2008) studied the presaccadic buildup of visual attention allocation at the saccade goal. By varying the time of onset of the discrimination target, the author found that attention was gradually deployed to the saccade target until it reached a maximum shortly before movement execution. Moreover, Rolfs, Jonakaitis, Cavanagh, and Deubel (2012) found that prior to a sequence of two saccades attention is allocated to the upcoming postsaccadic retinal location of the second saccade goal location. It is assumed that activity on retinotopically organized spatial maps of attentional allocation is remapped in a predictive manner to account for the saccade-induced change in retinotopic target locations (see also Duhamel, Colby, & Goldberg, 1992).

1.4. *The current work*

Selection of visual information can be described as a result of competition between sensory inputs for limited processing resources (e.g., Bundesen, 1990). Selection of visual information is needed for both the recognition of objects as well as visuomotor behavior (e.g., Desimone & Duncan, 1995). Moreover, there is evidence that selecting visual information for object recognition and for deciding "where-to-look-next" relies on a common attentional mechanism (e.g., Deubel & Schneider, 1996).

The retinal input from which Visual Attention has to select relevant information within a fixation is discontinuous, both temporally as well as spatially. That is, at a specific point in time several objects may be present at variable locations, while at a specific point in space several objects may be present at variable points in time. In order to select relevant information (i.e., a target) among irrelevant, yet competing, information, processing resources thus need to be distributed within space and across time. This has been addressed in studies on the temporal spatial dynamics of Visual Attention.

Performing everyday tasks strongly requires sampling visual information across multiple fixations, i.e., transsaccadically (cf., Land & Tatler, 2009). Therefore, the retinal location of a target is typically altered through overt selection, i.e., an eye movement. Thus, even though an object's location may be stationary within a fixation its retinotopic location can change by virtue of an eye movement.

Despite these changes of visual information within a fixation or by means of eye-movements, Visual Attention needs to be allocated to relevant information until it has been sufficiently processed so that it is useful to object recognition (e.g., for verbal report) and to visuomotor control (e.g., for executing an eye-movement).

For these reasons, it appears highly relevant to consider the interaction of the two orienting mechanisms when attempting to study the temporal and spatial dynamics of Visual Attention. Moreover, given the fact that humans can produce up to four saccades per second, Visual Attention is required to resolve competition efficiently within a very brief duration. The experiments presented in the current work address these issues by studying processing of multiple targets that are distributed across space and time both within a fixation and across two successive fixations. Depending on the tasks, these targets could be relevant to visuomotor behavior, object recognition, or both. The current work addresses two main topics. First, the present work aims at a better understanding of the temporal as well as spatial characteristics of how Visual Attention selects and maintains information for object recognition and visuomotor behavior. To what degree does processing within these two functional domains rely on common attention mechanisms? Second, laboratory research on these mechanisms of Visual Attention has mainly been concerned with competition within a fixation. This not only holds for interference phenomena such as the Attentional Blink but also for the presaccadic coupling of Visual Attention and eye-movement control. More specifically, a transsaccadic perspective on visual competition is lacking. Therefore it is additionally studied how selection works when relevant information has to be gathered across successive fixations.

The following three paragraphs will briefly introduce the specific research questions of the current dissertations' three studies.

Some research indicates that the visual system processes spatial, respectively, object identity information separately (e.g., Ungerleider & Mishkin, 1982). Conversely, object recognition and eye-movements seem to rely on a common attentional mechanism. To what degree do presaccadic object recognition and localization (i.e. a computational requirement of an eye-movement) depend on a common selection mechanism? In the ***first study*** of the current dissertation this question is addressed by investigating how localizing a peripheral target interferes with identifying a centrally presented letter target. The two experiments measure the dynamics of attentional allocation for localizing a memory-guided saccade target by varying the temporal delay between the two targets. The time course of attentional allocation for identifying two sequentially presented objects has been studied in Attentional Blink or Dwell Time paradigms. By adopting the logic behind these paradigms the current study also tests whether this interference phenomenon can be found when both targets belong to different functional domains of pattern recognition and spatial computations.

The ***second study*** seeks to extend the findings on the presaccadic coupling of covert and overt orienting. When preparing a saccade Visual Attention is allocated to the goal location of the saccade. This allocation of processing resources is thought to be of relevance for the preparation of the eye-movement but also for identifying the visual information at the saccade target. Thus selection-for-perception and selection-for-action are coupled presaccadically. Does this coupling persist across a saccade? If this was the case, Visual Attention should be spatially biased towards the postsaccadic goal location of movement despite changes in its retinal location? This would show that the presaccadic coupling also exists across successive fixations, i.e., transsaccadically.

The Attentional Blink is typically studied within a single fixation. The ***third study*** tests whether this interference for identifying a second of two targets is also apparent across successive fixations. In this experiment a first target is presented presaccadically while the second target appears postsaccadically at a different location. A transsaccadic Attentional Blink should be observable in a reduced probability of identifying the postsaccadically presented object. The Attentional Blink is often attributed to attentional processes that transform the visual information into a durable format. A transsaccadic second target deficit might indicates a certain independence between Visual Attention and eye-movements, that is, attention demanding recoding is possible despite executing the overt orienting response.

Study 1 shows that the attentional requirements of localizing a peripheral target for a saccade task interferes with foveal object recognition in an Attentional Blink-like fashion. Study 2 indicates that attention facilitates object recognition at the postsaccadic goal location of a saccade. In study 3 attentional limitations in identifying two objects also exist when the targets are presented in successive fixations.

2. *Empirical Part*

Manuscript 1:

Griffiths, G., Herwig, A., & Schneider, W.X. (2013). Stimulus localization interferes with stimulus recognition: Evidence from an attentional blink paradigm. *Journal of Vision*, *13*(7):7, 1-14.

Manuscript 2:

Griffiths, G., Herwig, A., & Schneider, W.X. Visual attention and eye movements: Evidence for a transsaccadic coupling. *Manuscript submitted for publication in Nature.*

Manuscript 3:

Griffiths, G., Herwig, A., Quante, L., & Schneider, W.X. Dual Target Interference across Successive Fixations: A Transsaccadic Attentional Blink. *Manuscript submitted for publication in Psychonomic Bulletin and Review.*

3. *General Discussion*

The ***first study*** of the present dissertation tested the attentional requirements of localizing a target for a memory-guided saccade. Localizing a stimulus in the periphery can be considered a requirement of any goal-directed space-based motor action (e.g., eye or hand movements). While other studies (Deubel & Schneider, 2003) could show that a delayed goal directed eye-movement requires on an ongoing allocation of Visual Attention to the saccade target, this study tested how Visual Attention is involved when the movement target has to be memorized, i.e. transformed into a durable short term memory representation. Therefore, in two experiments the Attentional Blink paradigm was adopted. Typically, this paradigm involves pattern recognition of two trailing targets. By probing the ability to recognize a foveally presented letter at variable intervals after the presentation of a peripheral localization target, we found that localizing this stimulus in the periphery interferes in an Attentional Blink-like fashion with a letter recognition task. The attentional requirements of the localization task led to task-independent as well as task-dependent interference for the letter recognition task, depending on whether the localization target competed with other location distractors. The pattern of interference is interpreted on the basis of a common attentional resource for pattern recognition and spatial computations. Moreover this study shows that an Attentional Blink is not limited to selection-for-perception but can also be observed when the first target requires selection-for-action.

The ***second study*** evaluated whether presaccadic target selection biases postsaccadic selection for object recognition. Several studies have shown that saccade preparation obligates the allocation of visual attention to the goal location of the eye-movement (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). Thus, presaccadic selection for object recognition and saccade target selection is spatially biased to one location. Instead of presenting the saccade target and the perceptual target within the presaccadic interval, presentation of both targets in the current study was separated by a saccade. Postsaccadically the perceptual target was either presented at the same location as the saccade target, or at a different location within the foveal range. It was found that postsaccadically, Visual Attention is allocated in an obligatory fashion to the goal location of the preceding saccade. This facilitation of perceptual processing was independent of the perceptual target's retinal distance to the fovea. Thus, not the actual, but the intended landing position was critical for perceptual performance. Overall this indicates that the coupling of covert and overt selection mechanisms operate in a complex fashion across a saccade.

Finally, the ***third study*** addresses a transsaccadic Attentional Blink. As outlined in the introduction, the Attentional Blink refers to the time course of interference for identification of a second of two targets lasting around 500ms. In human vision, the frequency of up to four saccadic eye-movements per second suggests that this interference should affect target processing across more than one fixation. In order to study systematically the effect of T1 processing in one fixation on T2 processing in a trailing fixation, this study also took into account the interaction of covert and overt orienting. Participants had to perform a goal-directed saccade. During the presaccadic interval, T1 was presented at the saccade's goal location. T2 was presented postsaccadically at a different location. It was found that processing T1 in the presaccadic fixation interferes with processing T2 in the postsaccadic fixation. Moreover, T2 performance was also diminished for a control group who only had to perform the eye-movement and report T2's identity. The latter suggests an effect of postsaccadic attentional allocation, which is related to the findings from Study 2 of the current dissertation.

In the following, the results of all three studies will be discussed with respect to the temporo-spatial dynamics of Visual Attention for object recognition and visuomotor control. Furthermore, by relating the findings of the current work this discussion seeks out common mechanism in overt and covert orienting. The final section will briefly discuss the role of visual competition for transsaccadic perception.

3.1. *The temporo-spatial dynamics of Visual Attention for object recognition and visuomotor control*

The current work exemplifies basic attentional mechanisms which resolve competition among information that is distributed within space and time. The three studies suggest that selection-for-perception and selection-for-action rely on a common attentional resource. In the following, two aspects of attentional allocation will be discussed. In the first part, the mechanism that allows maintaining a briefly presented object despite visual competition within and across saccades will be considered. The second part discusses the role of obligatory and automatic attentional control over visual processing in the current findings.

3.1.1. *Attention for visual recoding*

In the first study we found that localizing a target can interfere with pattern recognition in an Attentional Blink-like fashion. Thus, the localization task required that attentional resources are allocated to the relevant location for a certain duration. Importantly, the demand for attentional resources decreased with increasing onset asynchrony of the two targets. In this respect the attentional requirements of a memory-guided saccade seem to differ from a delayed saccade (i.e., where the saccade target remains visible), which has been suggested to rely on an ongoing allocation of Visual Attention to the saccade target (Deubel & Schneider, 2003). It also appears that the selected location is not maintained in short-term memory, via an ongoing allocation of Visual Attention to the targets' location (Awh & Jonides, & Reuter-Lorenz, 1998; Awh & Jonides, 2001). Rather a mechanism is required that transforms T1's location into a durable format. More specifically, the results suggest that once the target is recoded, visual processing resources are released. Thus, explaining the difference in T2 performance for short and long target onset asynchronies. Such a short-term-consolidation process has also been proposed to explain findings on the Attentional Blink (e.g., Chun & Potter, 1995, Jolicoeur & Dell'Aqua, 1998), which is typically seen as reflecting limited resources for object recognition, i.e., selection-for-perception. Hence, by showing that such a process is also necessary for memorizing a location, Study 1 suggests that attentional resources required for this transformation are mutual across object recognition and visuomotor control systems.

The results of Study 3 indicate that recoding a presaccadically presented object into a durable format affects the amount of resources available for processing a second target after a saccade. Thus, it is possible to allocate attentional resources to a location for a saccade task (e.g., Deubel, 2008), while at the same time recoding the object at that location into a durable format. Interestingly, the results from Study 3 show that more attentional resources were required for a longer duration in the saccade plus recoding task as compared to the saccade only task. Therefore, allocating Visual Attention to the saccade target might be obligatory (Deubel & Schneider, 1996; Griffiths, Herwig, & Schneider, submitted) but this allocation does not necessarily lead to recoding of the object into a durable format. It is important to note that in Study 1, a task-dependent second target deficit was only observed when the localization target competed with localization distractors. In Study 3 the T1 mask may be seen as a functionally equivalent competitor. T2 performance with an unmasked T1 in the study 1 paradigm should not differ from the saccade-only condition.

Together, these findings suggest that allocating Visual Attention for spatial computations, respectively, saccade target selection is dissociable from recoding an object or a location into a durable format, yet both processes rely on a common Visual Attention resource. Whether an object or a location requires recoding seems to depend on visual competition.

3.1.2. *Automatic and obligatory attentional control*

In the following, the nature of control over Visual Attention allocation in three studies will be discussed. Typically, research on Visual Attention relies on a dichotomy of task-driven and stimulus-driven control. Besides requiring goal-directed Visual Attention, all three studies revealed an automatic component of attentional control, in the sense that the allocation of Visual Attention was not under voluntary control (cf., Egeth & Yantis, 1997).

Study 1 and 3 showed that T2 processing was affected even when T1 (i.e., the localization target in Study 1 and the letter identification target in Study 3) did not have to be reported, i.e. when they could be ignored by the participants. Thus, descriptively there is some communality. However, are the underlying mechanisms of these second target deficits related?

Study 1 explains the task independent second targets deficit by assuming that Visual Attention was allocated to the localization target in an automatic fashion. The second target deficit for the control group of Study 3 is explained on the basis of the postsaccadic coupling of Visual Attention to the saccade target found in Study 2. The latter was also suggested to be an obligatory allocation of attention to the saccade target location. Some findings (e.g., Smith, Rorden, and Jackson, 2004) suggest that exogenous Visual Attention is more strongly related to eye-movement control than endogenous orienting (for an overview see, Smith & Schenk, 2012). Thus, the involuntary covert orienting effects in the current work – that is, towards the sudden onset in Study 1 as well as the postsaccadic allocation of Visual Attention to the saccade target in studies 2 and 3 - might reflect an overlap in cognitive control systems for exogenous attention and eye-movements. Conversely short-term memory consolidation could reflect a mechanism that relies on endogenous Visual Attention, more or less independent of occulomotor control (but see Carbone & Schneider, 2010, for results that indicate that exogenous orienting and short-term memory consolidation rely on a common resource). Independent control over Visual Attention could also explain why executing an eye-movement is possible while a target is still undergoing short-term memory consolidation, as in Study 3.

However, it appears difficult to apply a strict dichotomy of top-down and bottom–up driven attention, as it would not capture properly the nature of control in these findings. More specifically, postsaccadic allocation of Visual Attention in Study 2 seemed automatic yet it was essentially task-driven, and thus not bottom-up controlled. A possible mechanism which was proposed in Study 2 to explain this finding was an allocation of Visual Attention based on an efference copy signal (von Holst & Mittelstedt, 1950) of the eye movement, i.e. motor prediction. Typically, a motor command is seen as a result of sensory processing. An influence of a motor command on perceptual processing is currently not considered in models on the interaction of attention and action (e.g., Schneider, 1995; Schall & Woodman, 2012). In general, a strict dichotomy of attentional control along stimulus driven and goal-directedness has been criticized (Awh, Belopolsky, & Theeuwes, 2012), and models of Visual Attention might thus need to reconsider the idea of control in order to encapsulate other influences on selection-for-perception, such as motor prediction. The latter seems especially significant for the close interaction of covert and overt orienting. In this sense the coupling of Visual Attention and eye-movements is obligatory because it is based on a common goal. More generally this stresses the important role of intentions in the control of perception and action (e.g., Prinz, 1997, Herwig & Waszak, 2009).

3.2. *Implications for transsaccadic perception*

Visual information is gathered across several fixations. This leads to the question of how the visual system integrates, differentiates but also maintains parts of the visual environment transsaccadically. This has been addressed as the problem of transsaccadic perception (e.g., Irwin, 1991; Melcher & Colby, 2008). The studies presented in the current dissertation offer insights into two attentional mechanisms that resolve competition transsaccadically. How are these related to concepts and findings from research on transsaccadic perception?

The first mechanism was revealed in Study 2 of the current work. It was shown that the visual system is able to maintain a transsaccadic spatial bias towards the saccade target location. Moreover, this bias worked in a spatially highly specific manner, i.e. targets were separated by only half a degree of visual angle (i.e., about 10% of the saccades amplitude). This is interesting because previous research on transsaccadic perception could show that participants are unable to detect comparably large displacements of an object's location when it occurs during a saccade (for an overview see Bridgeman, Hendry, & Stark, 1975). The latter was long taken as evidence that detailed spatial information was not maintained across a saccade. However, later Deubel, Schneider, and Bridgeman (1996) showed that detection of the object's displacement improves dramatically when it is preceded by a brief blank period. Thus indicating that the visual system can access detailed spatial information across a saccade, but this information is not generally available for conscious report. In this sense detailed spatial information may be accessible to the selection-for-action system (dorsal stream) but not within the selection-for-perception system (ventral stream). It would be interesting to see how a small displacement affects postsaccadic allocation of visual attention. The current results suggest that processing should be facilitated at the intended saccade target location irrespective of the displacement. Conversely a blank condition may cancel out the transsaccadic coupling.

The second mechanism reflects the ability to maintain visual information transsaccadically. In the current work this has been discussed with respect to short-term-memory consolidation (e.g. Jolicoeur & Dell'Aqua, 1998; Schneider, 2013), i.e. recoding visual information into a durable representation. Research on transsaccadic perception initially discussed whether visual information from one fixation is integrated transsaccadically with visual information from the following fixation via a visual sensory buffer (e.g. McConkie & Rayner, 1976, Jonides, 1982). While this integration hypothesis was rejected (e.g., Irwin, Yantis, & Jonides, 1983), later research highlighted a role of visual short-term memory in maintaining object information across saccades and establishing object correspondence (e.g., Irwin, 1991; Hollingworth, Richard, & Luck, 2008). The current work shows that consolidating objects in short-term-memory can be performed transsaccadically. Objects thus compete not only for limited resources with all available visual information in the current fixation, but also with ongoing resource demanding consolidation of objects presented in a previous fixation. Thus, the role of visual-short-term-memory in transsacadic perception may not only be understood in terms of object correspondence, but also in its influence on transsaccadic competition.

Together these findings suggest that competition for visual processing resources cannot solely be understood as selection within a fixation. Rather the process of prioritizing processing of visual information works transsaccadically, and is thus influenced by selection-for-perception as well as selection-for-action from the previous fixation.

3.3. *Conclusion*

Together the three studies show that Visual Attention is defined in terms of limited processing capacity, which has to be allocated to relevant information within space and time. All three studies highlighted common attentional mechansims in object recognition and visuomotor control. It was emphasized that visual attention is required to select certain locations or object in space. Moreover, consolidating locations or objects into short-term memory requires an ongoing allocation of visual attention across time. In two of the studies it could be shown that the allocation of visual processing resources is essentially transsaccadic, i.e., competition was not limited to processing within a single fixation.

The complexity of visual information processing contrasts the subjective impression that perception occurs in a seemingly effortless fashion. The current dissertation highlights that the visual system achieves the latter only by means of a sophisticated selection mechanism, i.e., Visual Attention. It distributes limited processing resources to relevant information within space and time. Functionally object recognition and visuomotor control seem to rely on common processing resources. These are not only shared among visual input within a fixation, but competition also depends on selection and maintenance of information from the previous fixation. Thus, the current work indicates that Visual Attention may best best understood in terms of a mechanism that selects but also maintains visual information within and across saccadic eye-movements. This can only be achieved intricate interplay of overt and covert orienting mechanisms.

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