Granularity of Cognitive Representations in Actions

Advances to the Cognitive Architecture of Actions

Dissertation
zur Erlangung des akademischen Grades
doctor philosophiae (Dr. phil.)
vorgelegt der
Fakultät für Psychologie und Sportwissenschaft
der Universität Bielefeld
durch
Heiko Lex, M.A.

Supervisor

Prof. Dr. Thomas Schack

Referees

Prof. Dr. Thomas Schack

Prof. Dr. Andreas Knoblauch

Hiermit erkläre ich an Eides statt, dass ich die Dissertation mit dem Titel ‛Granularity of Cognitive Representations in Actions – Advances to the Cognitive Architecture of Actions‛ selbständig und ohne fremde Hilfe verfasst habe. Andere als die von mir angegebenen Quellen und Hilfsmittel habe ich nicht benutzt. Die den herangezogenen Werken wörtlich oder sinngemäß entnommenen Stellen sind als solche gekennzeichnet.

Bielefeld, Dezember 2014 Heiko Lex, M.A.

Meinen Eltern

The following chapters have been published as scientific peer-reviewed journal articles

Chapter 2

This chapter is a revised version of Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2014). The functional role of cognitive frameworks on visuomotor adaptation performance. *Journal of Motor Behavior*, 46(6), 389-396.

Chapter 3

This chapter is a revised version of Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2012). Functional relationship between cognitive representations of movement directions and visuomotor adaptation performance. *Experimental Brain Research*, 223(4), 457-467.

Chapter 4

This chapter is a revised version of Lex, H., Schütz, C., Knoblauch, A., & Schack, T. (2015). Cognitive Representation of a Complex Motor Action Executed by Different Motor Systems. *Minds & Machines*, 25(1), 1-15.

Chapter 5

This chapter is a revised version of Lex, H., Essig, K., Knoblauch, A., & Schack, T. (2015). Cognitive Representations and Cognitive Processing of Team-Specific Tactics in Soccer. *PLoS ONE*, 10(2), e0118219.

Contents

General Introduction

CHAPTER 1

Preface

"The linguist Noam Chomsky once suggested that our ignorance can be divided into *problems* and *mysteries*. When we face a problem, we may not know its solution, but we have insight, increasing knowledge, and an inkling of what we are looking for. When we face a mystery, however, we can only stare in wonder and bewilderment, not knowing what an explanation would even look like" (Pinker, 1997, p. ix). Chomsky's idea of mysteries and problems reflects a conceptual distinction between both. A problem interpreted as a kind of a conceptual image of the environment seems to be understandable. A concept interpreted as a fixed cognitive structure has a scope and has limits. Mysteries, in contrast to problems, seem to lie beyond individual limits. Thus, problems are a matter of individual conceptual interpretation, whereas mysteries cannot be solved in that same way. The overarching idea is to break mysteries down into problems, and try to solve existing problems. The current thesis faces problems in the area of cognitive representations and their impact on motor actions. Surely, the presented results will introduce new problems and at best foster the progress in that research area.

Following Chomsky's approach that problems are a matter of individual conceptual interpretation, it seems apparent that the establishment of cognitive representations evolves based on cognitive sorting and categorization processes. Thoughts are one way to describe and understand cognitive representations, because they partly take place in a linguistic medium (Fodor, 1987; Fodor & Pylyshyn, 1988). However, a linguistic medium by itself is productive, and it is necessary attributing not to many properties to a representation that are normally used to talk about that representation (e.g., the temperature of things is finite, whereas the scheme to describe temperature, the real numbers, is infinite). Thus, words describing a representation do not deliver insight into the structure of a cognitive representation (Egan, 2012).

Gibson (1966, 1979) held the claim that cognitive representations integrate, for instance, certain affordances of objects. Thus, consistent higher order object properties that are invariant through movement and object orientation are encoded, for example, in the wavelength and intensity of visual information absorbed at the retina. These affordances are significant functional aspects of an object (i.e., a scissor as an object useful for cutting and pricking) which rely on individuals' experiences. Clark (1998) described cognitive representations as "action-oriented", because they define a situation in combination with an appropriate behavior to the situation. Consequently, the idea has grown that cognition is embodied, respectively embedded. Moreover, cognition is not only embodied, cognition is also responsible for voluntary movement execution, and human memory is able to distinguish between different movements categories (e.g., manual actions, complex actions, and interactions). This arbitrary classification of movements allows studying the responsible memory structures for the executed movements in different environmental settings.

In the current thesis, an overarching cognitive architecture of movement organization is able to describe cognitive building blocks of motor behavior with certain functions. It will deliver evidence that cognitive building blocks of movement organization possess comparable functions in the movement organization in different environmental settings. However, the main attention is on the problem of structure and dimensions of cognitive building blocks of action within movement organization. Thus, this thesis will elucidate the *granularity of cognitive representations* in movement organization. Therefore, the following sections present recent knowledge of movement organization for three movement-related complexity levels: manual actions, complex actions, and interactions. Subsequently, the findings shed light on the problem of categorization and architectural models of movement organization, before ending with the formulation of corresponding hypotheses.

Manual Actions

Manual actions are able to describe manifold facets of human beings, because they show an "impressive integration of capabilities to shape physical interaction, comprising all levels" (Schack & Ritter, 2009, p.242).It begins on a local level with the regulation of certain finger movements to manipulate objects (e.g., using a pinch grip) evolving to more complex grasp patterns to learn about object properties (e.g., shapes, weight etc.)and ends with the estimation of certain action affordances. At a more global level, hand-eye or bimanual coordination ending in goal-directed action sequences characterize manual actions. Thus, higher order conceptualization is necessary to characterize manual actions touching the area of social science in terms of action semantics, intentionality, and communication (Schack & Ritter, 2009). Still, the control of degrees of freedom (DoF) and the coordination of different muscles innervating fingers and hands are complex cognitive tasks, which the motor systems needs to solve. One possibility to describe how cognitive control mechanisms in the field of manual actions work, is the investigation of the human adaptation behavior. Cognitive mechanisms play a multifaceted role in sensorimotor adaptation behavior

(Creem-Regehr, 2009; Mazzoni & Krakauer, 2006). Evidence comes from studies in which another task withdrew necessary cognitive resources (Eversheim & Bock, 2001; Taylor & Thoroughman, 2008), or when participants scored low on cognitive tests (Bock & Girgenrath, 2006).

The current thesis aligns manual actions primarily to adaptation processes. Various environmental conditions are able to disturb the motor execution of goal directed movements. To overcome such disturbances humans are able to adapt to certain environmental conditions and adjust their motor behavior appropriately. Thus, sensorimotor adaptation is an active learning process activated when motor actions differ from sensory consequences. This learning process lasts until the produced action effect and its perception will fit consistently together (Bock, 2001).Various implicit and explicit learning processes activated during the sensorimotor adaptation trigger such behavior (Mazzoni & Krakauer, 2006). Adaptation behavior in an ever-changing environment requires substantial modification capabilities of the human brain. The term "internal model" summarizes such modification capabilities. The *recalibration* of sensorimotor pathways and the use of *strategies* (i.e., anticipation, changes in attitude etc.) establish an appropriate internal model. Internal models are not located at a certain brain area. Instead, they are one of many functions of a distributed neuronal system responsible for motor control. An internal model describes spatial and dynamic features of the human environment (including the own body), updates itself constantly through multisensory inputs, and provides this information to the motor system for an adequate movement organization (Bock, 2001). Changes in the internal model are difficult to manage for the human brain. The managing process in the human brain varies qualitatively and quantitatively. Principles of internal model adaptivity will shed light on these facts.

Acquired adaptive changes remain in the human brain for a task-dependent length of time. Humans who adapted towards a defined distortion were able to start nearly at the same level where they stopped the last time (Krakauer, Ghilardi, & Ghez, 1999; Shadmehr & Holcomb, 1997), even when there is one month between test and retention test (Bock, Schneider, & Bloomberg, 2001). The authors concluded that the learned internal model persists over time, and will be retrieved if necessary. In addition, an already learned distortion is able to generalize to untrained, but similar distortions. This generalization affects untrained movement amplitudes (Bock & Burghoff, 1997), untrained directions (Krakauer, Ghilardi, & Ghez, 1999), and untrained areas of the work space (Shadmehr & Moussavi, 2000). However, the power of the generalizability is strongly dependent on the bandwidth of training (Bock, 2001). Moreover, an internal model adjusts gradually towards similar distortions. The adaptation towards a distortion of the visual feedback in terms of 90° rotation revealed a smaller error for a 60° pre-adaptation as compared to a 45° pre-adaptation or no pre-adaptation at all (Abeele & Bock, 2001). These results suggest that humans possess the ability to retrieve information from former settings and adjust them to a recent movement problem. Additionally, internal models exhibit a modular structure. The adaptation towards a combined visual-proprioceptive distortion is faster for participants who adapted towards both distortions separately (Flanagan, Nakano, Imamizu, Osu, Yoshioka, & Kawato, 1999).Internal models need a certain amount of time (i.e., a number of repetitions) to adapt towards unknown distortions. Rest breaks between trials need to last at minimum 5 s. Shorter rest breaks have a negative impact on the time needed for proper adaptation towards a distortion. It seems as if humans need some time to reflect what they actually did to cognitively process behavioral changes (Bock, Thomas, & Grigorova, 2005).

The mentioned studies suggest that sensorimotor adaptation is controlled based on cognitive mechanisms. The internal model hypothesis is one attempt to describe sensorimotor adaptation behavior in sense of cognitive functionality. However, the functional role of cognitive aspects of movement organization in sensorimotor adaptation is still an open issue. More precisely, the investigation of relevant cognitive representation structures in manual actions is going to convey the knowledge in the area of sensorimotor adaptation. However, humans are able to express intentionality and action-semantics by manual actions. Thus, manual actions are often an integral component of complex actions.

Complex Actions

The volitional structuring of complex actions with regard to goal orientation is a crucial dimension of complex actions. A corresponding psychological unit that orientates itself at the realization of such action goals describes complex actions(Müsseler, Aschersleben & Prinz, 1996; Nitsch, 2000). The reference framework for the definition of action complexity contains of goal-orientation and connection to different levels of action control. Schack (2010) suggests two representation levels for action control, where both are capable to organize action execution by itself. The level of sensorimotor control executes more or less autonomous processes. The level of mental control connects the anticipated goal of a movement with produced action effects. Manual actions, like pointing movements in a two-dimensional space (see Chapter 2 & 3), are learned very quickly, because only a few DoF need to be controlled. This movement gets a status of automation within a few repetitions. Thus, the level of sensorimotor control executes the movement with only a temporal involvement of mental control. However, the proper execution of an instep kick in soccer demands the motor systems to control several movement problems (e.g., generation of speed, approaching to the ball, kicking the ball with the instep, preparation for subsequent actions). Therefore, a goal-oriented and volitional coordination of single movement sequences is necessary to manipulate the ball. Thus, the motor system needs to control several DoF in complex actions (Schack, 2010).

The investigation of cognitive representations of complex actions has two approaches. The first approach includes a phenomenological perspective, and the second approach a functional-analytic perspective. Both approaches use different techniques to describe cognitive processes responsible for movement organization. The phenomenological approach uses less standardized empirical techniques (e.g., interviews, questionnaires, ordering techniques). These techniques have the major problems to assure objectivity, reliability, and validity in the test settings (Thomas & Thomas, 1994). Especially, interviews (Miles & Hubermann, 1994) and ordering techniques (Scheele & Groeben, 1988) depend heavily on the experimenter who is interpreting participants’ answers. The functional-analytic approach assumes that participants are unable to explain their representation of complex actions explicitly. Thus, qualitative research methods are able to complement quantitative research methods. An example for these relatively "new" methods are neuroscience techniques. Under the scope of neural science, different techniques, like functional magnetic resonance imaging (FMRI), electroencephalography (EEG), or near-infrared spectroscopy(NIRS) investigate mechanisms of the neural system (Kandel, Schwartz, Jesell, Siegelbaum, & Hudspeth, 2012). A distinct research area focuses on the link between cognition and movement execution. Cross, Hamilton, and Grafton (2006) showed that, when "dancers observed and simulated another dancer's movements, brain regions classically associated with both action simulation and action observation were active" (p. 1259). This finding suggests that a five-week intensive training program helps to establish a new complex motor representation. Hauk, Johnsrude, & Pulvermüller (2004) showed via neuroscience techniques that the reading of action words (i.e., verbs like lick, pick, and kick) already activates brain regions associated with the corresponding organ (e.g., face, arm, and leg). Additionally, EEG-techniques investigated the neural activity during goal-oriented power grips. The results suggested a similar parieto-frontal network activation pattern as for precision grips except a distinct temporal pattern (Westerholz, Schack, & Koester, 2013; Westerholz, Schack, Schütz, & Koester, 2014). Consequently, a similar activation pattern for power and precision grips delivers evidence for a comparable representation network in the human brain.

A theoretical perspective of movement organization in memory describes two major directions: sensorimotor frameworks and ideomotor frameworks. Sensorimotor approaches consider stimulation as the starting point for actions. "Actions are considered responses to stimuli that precede them" (Prinz, 2005, p.141). The ideomotor approach postulates that intentions are the starting point for actions. “Actions come into being as the means for realizing those intentions” (Prinz, 2005, p.141). The ideomotor approach grounds on ideas of voluntary action execution (Lotze, 1852; James, 1890). Two conditions characterize the ideomotor approach: (1) there exists an idea (i.e., representation) of a volitionally executed action, and (2) conflicting ideas (i.e., representations) are inhibited. “When these two conditions are fulfilled, the representations of the intended goal states have the power of generating the action directly” (Prinz, 2005, p.142). The ideomotor principle bases on such representations.

The investigation of anticipatory behavior seems to be a promising approach in bridging the gap between situated action and cognitive representation (Pezzulo, Hoffmann, & Falcone, 2007). Anticipation allows a stabilization of perception and a goal-oriented behavior with the aim to improve adaptivity of humans to environmental conditions. Thus, perceiving as well as acting refers to external events and relies on the same representations, which are represented by *common codes* (Schütz-Bosbach & Prinz, 2007). A study investigating basketball free throws found evidence for the link between action observation and action execution (Aglioti, Cesari, Romani, & Urgesi, 2008). Basketball experts (possessing high visual and motor experience) predicted the outcome free throws in basketball earlier compared to journalists (possessing only visual expertise)and novices (possessing no expertise). Thus, within a field of expertise a functionally organized representation structure facilitates movement execution, and supports movement perception and anticipation of movement effects. That holds true for representations in the own field of expertise, and is not transferable to other (biomechanically) similar domains (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Calvo-Merino, Grezes, Glaser, Passingham,& Haggard, 2006). The results of these studies deliver evidence for two conclusions: First, the observation of movement patterns similar to the own field of expertise activates similar neural structures. Second, the activation is higher when a movement pattern identical to the own field of expertise is presented.

However, a detailed description of how cognitive representation are stored in memory seems to be necessary for a further understanding. Therefore, research focused on the storage of information in human LTM (Janelle & Hillman, 2003; Munzert, 1995, Starkes & Allard, 1993; Starkes & Ericsson, 2003; Starkes, Helsen, & Jack, 2001). The used methods were assigned to qualitative research (e.g., interview, questionnaires, and categorization tasks) including the described problems with reliability and objectivity (Thomas & Thomas, 1994). Therefore, a new line of empirical research focusing on the functional link between performance outcome and LTM structures needed to be established. A research method called *structural dimensional analysis of mental representations* (SDA-M; Schack, 2002, 2012; Schack & Ritter, 2009) allows the investigation of cognitive representations of complex actions in LTM. This method revealed differences between expert and novice cognitive representation structures of the tennis serve in their LTM. There were only small differences between the representational frameworks (i.e., cognitive representation structure) within each expertise level. The cognitive representation of the tennis experts, as compared to tennis novices, reflected the biomechanical and functional demands of the task (Schack & Mechsner, 2006). Other studies replicated the results in domains of dancing (Bläsing, Tenenbaum, & Schack, 2009), judo (Weigelt, Ahlmeyer, Lex, & Schack, 2011), and health sciences (Braun, Beurskens, Schack, Marcellis, Oti, Schols, & Wade, 2007; Wollesen, Lex, & Mattes, 2012). The cited research studies used basic action concepts (BAC) as conceptual representation units, which corresponded to "functionally meaningful submovements" (Schack & Mechsner, 2006, p.77). BACs are cognitive clusters of movement impulses with their corresponding sensorial effects in terms of a functional equivalence during the solution of a movement problem. BACs combine functional movement features. BACs are describable through various surface structures (in form of labels). These labels are, for instance, verbal, acoustic, kinesthetic, and visual labels. Therefore, BACs are describable through verbal expressions, optical depictions, muscle senses, and hearable movement by-products. Thus, every label refers to the identical cognitive unit within each BAC (Schack, Stöckel, & Weigelt, 2008). It seems appropriate for the proper execution of complex actions to coordinate all DoF of the whole body in a functional way. Studies revealed that a functional cognitive movement organization facilitates such a coordination process (Bläsing, Tenenbaum, & Schack, 2009; Schack & Hackfort, 2007; Weigelt, Ahlmeyer, Lex, & Schack, 2011). Because complex movements require exactly definable and biomechanically describable affordances, the amount of functional relevant BACs is narrow. Furthermore, previous motor experiences facilitate an appropriate movement execution, because BACs including the corresponding sensorial experiences are already established (Schack, Stöckel, & Weigelt, 2008). Thus, a kind of "movement library" filled with BACs exists in human LTM. Assuming that such a storage unit is located in human LTM, existing representation structures facilitate the learning process of new similar movements.

Interactions

Movements are the way in which humans interact with each other. Regardless, if we are attempting to catch a cab drivers attention in a crowded street, if we speak to a colleague, or if we smile at our partner. The motor system mediates such processes through arm gestures, speech, and facial expressions to provide a common code for communication (Wolpert, Doya, & Kawato, 2003). A recent theory describes a mechanism, which maps perceived motor actions onto observers' motor experiences to decode the information. Research in the field of neuroscience delivers empirical support for such a hypothesis with the finding of "mirror neurons". These mirror neurons are activated in both action execution and action observation (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti & Arbib, 1998; Gallese, 2003). Even the reading of action words (i.e., verbs) activates the pre-motor system (Hauk, Johnsrude, & Pulvermüller, 2004). Moreover, the naming of tools activates brain regions that are associated with the corresponding imagined hand movements and the corresponding action words (Martin, Wiggs, Ungerleider, & Haxby, 1996). Such empirical data makes the motor system to an object of research for action interpretation and social interaction. There are parallels between the mechanisms that occur in motor control, action observation, imitation, and social interaction (Wolpert, Doya, Kawato, 2003). The basic motor control process describes a feedback loop between motor commands including muscle contractions that change the body state and a steady sensory feedback that influences following motor commands. However, an identical motor command is able to trigger different consequences (e.g., if the muscles are fatigue depending on pre-exercises). The sensory feedback of a motor action enables the central nervous system (CNS) to estimate a correction function for the next motor command (Wolpert, Doya, Kawato, 2003). Supposedly, a similar feedback loop characterizes social interactions. A communicative action (e.g., speech, gesture, facial expression, or other body language) substitutes the motor command. The interaction partner provides feedback about the communicative action, which humans interpret to change their mental state (Wolpert, Doya, Kawato, 2003). At the end, we are able to adjust our next motor action. In a word, the way humans thinks about others' actions to engage in social interactions, depends on the way in which humans activate and simulate their own motor actions (Jeannerod, 2001). Thus, motor cognition includes processes involved in human's motor execution (e.g., planning, preparation, and production),and motor cognition includes processes involved in anticipation, prediction, and understanding of other humans' actions. These processes work predominantly at an automatic, covert, and unconscious level (Sommerville & Decety, 2006).

Shepard (1984) claimed that perceived patterns resonate in observer's memory. Thus, the resonance mechanism describes the decoding of perceived triggers in observer's memory to understand environmental conditions. The resonance mechanism and the cognitive representation work consistently together. The perceived patterns are deeply internalized(i.e., as representations) and can be activated without any environmental information (e.g., mental imagery). Thus, cognitive representations of motor actions refer to both (1) the action goal or action effect and (2) to operations prior to motor execution. "There are no ontological reasons to consider these two levels of description as separate or, least of all, independent from one another" (Sommerville & Decety, 2006, p.180).

However, the ability to represent single motor actions of our own and others does not necessarily mean that they are limited to the next upcoming effect in a constraint chain of events. Rather, humans possess the ability to build cognitive representations of actions that are interrelated. These related actions form event representations to share common features and characteristics (Zacks & Tversky, 2001). To some degree, event representations are similar to object representations (Mervis & Rosch, 1981).Humans tend to organize motor actions with regard to the context in which it is applied. Humans can construe a simple motor action (e.g., grasping the lock of a bike) at various stages of analysis: in terms of unlocking the bike, in terms of riding to the grocery, or in terms of organizing a party. Adults incorporate such hierarchical analysis level in their action representations (Zacks, Tversky, & Iyer, 2001).

Acquired memory structures representing hierarchical action sequences depend highly on the level of expertise. The quantitative degree of the hierarchical problem-solving process, for instance in chess (in terms of number or speed of pre-calculated moves) measured by *think-aloud protocols,* did not differ significantly between chess experts and average players. However, the recall of shortly presented chess constellations was an indicator for the level of expertise (De Groot, 1978/2008). Chase and Simon (1973) presented chess constellations with randomly assigned figures or really played chess constellations. In the played constellations, experts accessed their chess-specific expertise, and outperformed average chess players. Thus, chess experts are able to memorize chess constellations better than average chess players are (Gobet & Simon, 2000).

Chess experts represent the context hierarchically (i.e., the evolution of certain moves in chess) in terms of tactical constrains.

In the context of sport games, such hierarchical action representations can describe, for instance, chains of dependent motor actions in terms of tactical behavior at an individual, group, and team level. For example, a soccer player comes in possession of the ball through a team-specific behavior (e.g., change sides). After that successful change of sides, a defender wants to get the ball and tries to tackle the player. The player perceives one teammate in a favorable position. At group-specific level, the player decides to play a give-and-go pass with his teammate to overcome the defender’s action. Therefore, the player decides to use an inside kick as a situation-adequate complex action at individual level. Thus, tactical behavior integrates the activation of various representations at different stages (individual, group, and team level). As a logical consequence, the structure of consecutive following motor actions forms the representations of tactics. It seems plausible that a representation of team-specific tactics form the basis for strategic concepts. In consequence, this hierarchical order formation emphasizes a semantic structure of action sequences to tactics and strategies, which allows humans to access situation-adequate action sequences.

The choice for an adequate tactical behavior in sports bases on the perception of the intentions of other players (Nitsch, 2004). Players need to be able to anticipate the possible outcome of opponents and teammates intentions in advance (Aglioti, Cesari, Romani, & Urgesi, 2008). Thus, all relevant sensory information need to be available to choose for an adequate motor action (Bosbach, Prinz, & Kerzel, 2004). As described earlier, the structure of cognitive representations constrains the perception and evaluation of relevant sensory information. Therefore, tactic-specific action knowledge is of central importance for the playing competence of each player with an increasing level of expertise (Höner, 2005), and hence, might be organized in conceptual units in player’s LTM as tactical skills (Hodges, Huys, & Starkes, 2007; McPherson & Kernodle, 2003). Evidence for an advanced tactical skill comes from studies at a behavioral level. Adolescent soccer experts and novices judged real-time soccer scenes in a temporal occlusion paradigm regarding possible passing options. The authors concluded that soccer experts evaluate and prioritize the possible offensive tactical behavior better as soccer novices. In other words, soccer experts recognize the relative importance of single player positions on the pitch, and they are able to represent purposeful actions better as novices (Ward & Williams, 2003). However, this valuable research does not explain which cognitive mechanisms allow experts to act in a purposeful way. Thus, the relevant cognitive units stored in LTM are objects of research at the level of cognitive representations in interactions in the current thesis.

Categorization

Up to here, the current thesis described the role of cognitive memory units (i.e., representations) as an important factor in the organization and execution of motor actions. The structure of cognitive memory units characterizes different performance levels in the execution of manual actions, the performance of complex actions, and the creation of interactions. However, various theoretical models and methodological approaches describe and explain the investigated settings. This thesis works on the description of possible invariances and common features of representation units of manual actions, complex actions, and interactions.

The ability to form categories is an indispensable prerequisite for humans and animals. Imagine the incorrect assignment of a visually perceived part of an animal's fur to the category predator or to the category herbivore. Such an incorrect assignment can become crucial for the live of that individual. Thus, all organisms need to be able to assign environmental conditions to categories (Ashby & Lee, 1993).Many neural structures are involved in category learning processes in humans that depend only to some degree on the existing structure of categories within individuals. For example, the cognitive processing of learning new categories is different as compared to the processing of already learned categories (i.e., expertise). Evidence steams from studies on frontal lobe patients (e.g., Parkinson's disease), which are impaired in learning new categories, but are able to access the already learned ones, such as categories of fruits or tools (Ashby &Ell, 2001).

Therefore, an interesting question is which cognitive principles guide the categorization process. Two major principles exist: The first relates to the function of a category system. This function reduces the DoF of environmental conditions in the real world, and still provides a maximum of information. The second relates to the information structure and builds upon the first principle. The information structure turns unpredictable and arbitrary attributes of things in the real world into structured information in the observer's memory. Then, the retrieval of structured information is easy. Following these principles, the categories map the perceived world structure as closely as possible. Thus, cognitively meaningful and usable proportions reduce the infinite number of differences among stimuli in the environment. It is obvious that categorization processes are triggered based on consciously perceived stimuli (Rosch, 1978). For example, a dog smells things humans cannot, and the movement experience of the own motor system influences the way, in which movements of others will be interpreted. Thus, the number of actions treated as functionally equivalent in the motor system form a category of the reality in memory (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976).

Two dimensions of categories define the category formation within humans, a vertical and a horizontal dimension. The level of inclusiveness defines the vertical dimension of categories. For example, the dimension at which the terms field mouse, mouse, mammal, animal, and living organism vary. In that, the broadest level will be the most inclusive (i.e., living organisms). The segmentation of categories at the identical level of inclusiveness defines the horizontal dimension of categorization. For example, the dimension at which the terms mouse, cat, fox, and elephant vary (i.e., mammals). The horizontal dimension ensures the distinctiveness between category elements. These category elements tend to become prototypes that contain attributes, which are most representative for the items inside and least representative for items outside that category (Rosch, 1978). Categories have the most attributes in common with members of the same category, and the least attributes shared with members of other categories (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976).

In conclusion, conceptual domains of not arbitrary semantic categories develop around perceptually salient natural prototypes (Rosch, 1973). Humans are able to judge which case (i.e., in form of a prototype) is representative for a category even when they disagree about the boundaries of the same category (Rosch, 1975). Therefore, prototypes constrain a category, but they do not reduce a category to only one prototype (Rosch, 1978, p.200), and they are not equivalent to cognitive representations. Moreover, cognitive representations organize prototypes. An example is the representation of objects. Basic objects are the easiest to imagine, and the first named by small children. The representation of objects happens predominantly as members of their basic object category(Petersen & Graham, 1974; Rosch, Mervis, Gray, Johnson, & Boyes-Bream, 1976; Smith, Balzano, & Walker, 1978). The following statement sums up the aforementioned descriptions: "categorization is not the product of historical accident …but rather the result of psychological principles of categorization" (Rosch, 1978, p.27).

The relation between representation units determines the cognitive categorization (i.e., structure formation) of representations. The relation between different representation units bases on feature dimensions of these units. Schack (2010) labeled the assignment of features to representation units as *dimensioning*. The goal-oriented action effects including their reafferent sensory patterns form the dimensions of representation units. Thus, the representation structure expresses an internal grouping of representation units sharing common features into subgroups (Schack, 2010). The feature dimensions of representation units are responsible for the evolution of a network integrating action-relevant representation units. Such a network is the result of an effort-reducing structure formation in LTM. Additionally, for the reason that each representation unit integrates afferent sensory features and reafferent features these representation units are nodes in a network that spans a multidimensional space (Schack, 2010). As a converse argument, the representation structure allows the inference to feature dimensions of representation units in that network. The recent thesis elucidates such processes for three movement-related complexity levels (i.e., manual actions, complex actions, and interactions).

The Cognitive Representation

The reduction of the number of DoF to a system-specific and controllable amount by the establishment of functional cognitive representations is a prerequisite for motor action execution. To achieve the described functionality of cognitive representations the *classical view* makes five assumptions. (1) Cognitive representations describe mediating states of intelligent systems that carry information. Tverskys' contrast model of similarity describes object representations as sets of features. These features treated as symbols stand for distinguished object properties. Thus, the comparison of two objects leads to the definition of two sets of object properties. Features within the intersection of both sets of object properties describe similarities, and features outside the intersection describe variations of the two objects. Both entities compare the information of both objects in the representing world with each other (Tversky, 1977).(2) Cognitive systems require some enduring representations, because individual experience guides the representation system. Evidence for this assumption delivers the fact that some internal representation in the representing world endures longer as the counterpart in the represented world. For example, the representation of the color as an object feature(e.g., the color of a friend's car) is still present, even when the object color has already changed in the represented world (e.g., the friend bought a new car of different color). (3) Cognitive systems use symbols. Symbols are discrete packages of information, which are able to serve as features (e.g., a certain song serves as a symbol to remember an old friend). (4) Some cognitive representations align to specific perceptual systems, whereas other are amodal. Perceptually aligned representation relate to perceptual experience (e.g., taste of food). Amodal representations consist of complex interpretations(e.g., the representation of truth or justice). (5) Cognitive representations belong with no regard to a particular effector system. Moreover, the representations and the particular effector are partially decoupled. For example, writing letters is possible with the hand, but also with the foot or with a pen attached to another effector. The written letters remain recognizable. Thus, there seems to be no necessary connection between features that describe an object and the observed perceptual information.

However, additional theories enlarge the classical view of cognitive representation. An alternative approach is *embodied cognition*. This approach extended the classical view by the interdependence of the perceptual and the motor system. Pfeifer and Scheier (1999), for instance, built a wheeled robot without vision and only simple motor routines. This robot was able to generate a representation of the size of an object by measuring the speed ratio between the inner and the outer wheel while circling around that object. Nevertheless, in the embodied cognition approach exist limitations in modeling higher order representations. Alternative approaches to the classical view of cognitive representations, like embodied cognition, intertwine the perceptual and the effector system with each other. However, the embodied cognition approach still focuses on low-level perceptional and motor processes with limited success in modeling higher-order cognitive representations. This alternative approach combines the idea that cognitive processing involves mediating states that carry information, and adds something to the particular properties of the mediating states (Markman & Dietrich, 2000a). The limitations of the embodied cognition approach initiated a change of the classical perspective. An adequate cognitive model should be sensitive to perceptual representation and address the problem of the integration of low-level percepts and high-level thoughts. Boundaries between different representation levels are hard to distinguish and cognitive science should strive for a diversity of research methodologies that examine explanatory useful properties of cognitive representations. Such research should focus on cognitive representations and the integration of low-level perception and high-level thought in the development of human concepts (Markman & Dietrich, 2000b). The representation of such high-dimensional data causes the problems of dimensionality and structuring. It seems to be an unrealizable task for the central nervous system (CNS) to represent all possible configurations without using simplifying rules for motor control (Wolpert, Doya, & Kawato, 2003). However, in advance to the discussion of the problems of structure and dimensionality of representation units, it is necessary to introduce selected theoretical models of a cognitive architecture of actions.

The Cognitive Architecture

Herbart (1825) inferred from observation that only a certain area in the retina (i.e., the fovea centralis) is capable to extract reliable information from the environment, because humans see things clearly only in the fovea. Lotze (1846, 1852) and Volkmann (1846) rejected Herbart's theory based on the observation that it is possible to perceive things also in areas outside the fovea (i.e., periphery). Their theories base upon *visual local signs*. The first source of information is the pure qualitative system of visual sensations. The second source of information is a system of muscular sensations accompanying the eye movements. Environmental movements perceived in the periphery induce an eye movement of the fovea to that attractive point (i.e., the attention is shifted). The combination of the movement perceived in the periphery (visual sensation) in combination with the actual eye movement (muscular sensation) builds a spatial relation. Thus, visual local signs consist of the estimation of a spatial location from the linkage of the perceptual sensation of an interesting object and the muscular sensation of the corresponding eye movement. A genetic approach extended the idea of visual local signs (Wundt, 1898). That means that visual local signs result from a slowly evolving adaptation process, which facilitates the spatial experience of the observer. Since that period, actions are interpreted as reactions. Therefore, the prominent approach of *schema theory* including *generalized motor programs*(GMP) was postulated (Schmidt, 1975; Schmidt & Lee, 1998). However, GMPs differ from cognitive representations. For example, the description of features is less detailed, and the functional significance as a representation unit in the memory is more or less implausible (Konczak, 1996, 2002). There is a functional aspect in movement organization, which needs further attention. Learning a new movement requires to control all relevant DoF, and eliminate (i.e., keep constant) all irrelevant DoF. The cognitive system needs reduced and particularly useful proportions of the DoF(Bernstein, 1971). Thus, GMPs described in the schema theory are not an equivalent for motor action relevant cognitive representations, because they do not reduce the DoF (Bernstein, 1967).A more sophisticated approach named *ideomotor theory* assumed that movements are the result of goal states subtracted by current states (Prinz, 1987). Supposedly, if that is the case, only final configurations (i.e., action goals) are stored in the human memory (Jeannerod, 1997; Mechsner, Kerzel, Knoblich, & Prinz, 2001). Koch, Keller, and Prinz (2011) made a detailed description of the assumptions in the *ideomotor theory* and their impact on sport expertise. These and other recent ideas of the cognitive architecture of motor actions focused on the interdependency between cognition and action (Prinz, 1990, 1997, 2000). The *common coding approach*, for instance, described shared codes of motor actions and action-independent events by one specific representation (Hommel, Müsseler, Aschersleben, & Prinz, 2001). A fundamental approach termed *cognitive architecture of complex motor actions*, postulates the incorporation of intentionally guided representations in a cognitive framework (Schack, 2004b, 2010). The determining question focused on the integration of action related memory structures into a theory of behavioral control. The theory assumes that the cognitive system initiates the execution of new unknown movements, because sensory information about the unknown movement is not available. In the course of practice of the new movement, more and more sensory perceptions will be stored as sensorimotor representations. Therefore, different representational levels store different information of movement problem, and distinct representation level originate in the memory. Finally, the type of representations memorized at the corresponding level (i.e., mental or sensorimotor representation)specify the function of each level (Schack, 2010).Representation units possess an essential function within the memorization processes (Hoffmann, 1998; Munzert, 1997). More precisely, representation structures describe cognitive groupings (i.e., a network) of representation units with regard to the realization of action goals(Hoffmann, 1986). Schack (2004a, 2010) recommended BACs as functional representation units, because they integrate sensory and functional properties of complex motor actions. Table 1.1 presents the four hierarchical and functionally independent levels of action organization in the *cognitive architecture of complex motor actions*.

Table 1.1

Levels of action organization (adapted from Schack, 2004a, p.42)

Code	*Level*	*Main function*	*Subfunction*	*Means*
IV	Mental control	Regulation	Volitional control strategies	Symbols, strategies
III	Mental representation	Representation	Effect-oriented adjustment	Basic Action Concepts
II	Sensorimotor representation	Representation	Spatio-temporal adjustment	Perceptual effect representations
I	Sensorimotor control	Regulation	Automatization	Functional systems, basic reflexes

The first level is the level of sensorimotor control. The main function is the movement execution of highly automated movements and their spatiotemporal orientation. The main instruments are fixed functional movement systems and basal reflexes of the human organism. The second level describes sensorimotor representations. It is a representation level mainly concerned with the storage of sensorial characteristics of executed movements. The main instruments used at that level are perceptual codes. The third level describes mental representations, and forms another representation level. This level stores action-relevant BACs. The fourth level is the level of mental control. This level also represents a movement execution level, and implements both movement strategies and voluntary executed actions. The major instruments at this level are symbols and strategies (Schack, 2010). In general, this model seems to be highly dominated by the distal effects produced by voluntary executed motor actions. It describes the transfer from the intention-dominated cognitive system to the executing motor system for highly automated movements on the one hand, and guided voluntary movements based on environmental effects on the other hand.

The Problem of Granularity

The aforementioned insights into the cognitive architecture of complex motor actions (Schack, 2004b; 2010)pointed at an important issue. That is, how the proposed model deals with the problem of structuring and dimensioning of cognitive representation units. The cognitive architecture of complex motor actions consists of four functionally autonomous levels with particular regulation or representation functions. These levels interact with each other. Thus, relevant movement knowledge generates from existing representations and recent information of environmental conditions. The cognitive action representation forms a reference, which structures received information and activates mental representations in the memory (Schack, Stöckel, & Weigelt, 2008). The authors assume a functional autonomy between the different levels. Therefore, it seems plausible that functional variations at each level should have consequences for the whole system. Thus, cognitive representation units at the level of mental representation should exhibit qualitative differences (Schack, 2010).

Evidence for such an assumptions deliver the categorization processes in early infancy. The corresponding representations differ in kind with respect to the mental representation and the processes that operate on these representations (Eimas, 1995). Vygotsky (1934/1962) postulated that the earliest representations by children are idiosyncratic associations among things in their environment. Early infants build “cognitive heaps” from which meaningful and structured conceptual representations emerge during puberty. Piaget (1952) found that the earliest representations are sensorimotor representations. There is some evidence that the level of mental representation settles upon the level of sensorimotor representation (Klix, 1971). The level of mental control uses the functionality of the level of sensorimotor representation (Schack, 2010), and links the representations to selected terms (Prinz, 1983; MacKay, 1985). Terms are cognitive bundles of objector action features concerning the realization of actions (Hoffmann, 1986). The cognitive storage units at the representation levels are BACs (level of mental representation) and sensations (level of sensorimotor representation). BACs are responsible to transfer the anticipated action effect into an executable motor program (i.e., in terms of a spatio-temporal alignment). The dimensioning of BACs depends on the cognitive structures at the level of sensorimotor representations (Schack, 2010).

The level of sensorimotor representation stores modality-specific (re-)afferent information – information about perceivable sensations from sensory receptors (e.g., tactile, acoustic, visual, kinesthetic, proprioceptive, etc.) that accompany and/or follow movement execution. The stage of learning (i.e., level of expertise) influences the choice for the adequate sensory receptor (Meinel & Schnabel, 2007). Munzert (1989; 1992) described sensorimotor representations as motoric schemes in the form of sensorial effects. That research depended heavily on the schema theory postulated by Schmidt (1975). In summary, BACs as representation units are the representation unit, which integrates functional as well as sensorial features of action organization. Thus, the sensorial expertise at the level of sensorimotor representations determines the dimensions of BACs. In the progress of motor learning such sensorimotor representations shift from effector-dependent (categorial) to functional (appropriate for a task) dimensions (Schack, 2010). The mentioned approach describes representation units (BACs) as feature-oriented. Although it seems appropriate that BACs span a multi-dimensional space, which is constrained by the amount of functional, sensorial, and spatio-temporal features of complex actions. This approach is in line to the approaches formulated in the *classification of objects* by Mervis and Rosch (1981) and the *world of concepts* by Hoffmann (1986).

However, an open issue is the interdependency between two BACs (i.e., the internal structure), and how these are linked to each other during action execution. An example from BMX cycling will illustrate this. Two BACs from the main movement phase ("start rotation" and "head towards the front wheel") serve as an example. There is a connection between BACs (e.g., start rotation)and the corresponding sensorial features (e.g., muscle tenses, turns and twists, velocity of limbs, bike, head, etc.). The BAC "start rotation" ends with the preparation of all muscles in the back and the belly to lower the hip angle. The sensorial impression of the readiness of muscles forms the first sensorimotor representation of the BAC "head towards the front wheel". Thus, the sensorial features at the spatio-temporal ending of the first BAC forms the input features of the subsequent BAC. Such a network is the result of a cost-reducing structure formation in the LTM (Schack, 2010). The cost-reducing structure formation works also in self-organizing maps (SOM; Kohonen, 1997) and recurrent neural networks with parametric bias (RNNPB; Tani, Itob, & Sugitaa, 2004). These approaches are suited to map human motor behavior on technical platforms (Krause, Bläsing, & Schack, 2009).

In conclusion, BACs consist of the aggregation of sensorial feature dimensions. Therefore, new sensorial features modify existing BACs or evolve new BACs that are more useful in terms of functionality. That causes a change in structure formation in LTM. However, it is not clear yet, which parameters influence the formation of adequate BACs. As well, the schema (Schmidt, 1975) and the GMP-theory (Schmidt and Lee, 1998) did not have satisfactory answers to such questions.

The cognitive architecture of complex motor actions suggests the organization of regulation and representation levels with regard to the functional demands of the tasks. A corresponding goal state defines the functional demands of a task. The goal is a proper solution to the challenging movement problem. The instrument to achieve the goal is the functional cognitive representation (Schack, 2010).A functionally organized cognitive representation structure consists of groups of BAC aligned with functional movement phases. Göhner (1979) specified main phases and supporting phases (first and second order). This phase structure is linked to the solution of certain parts of the movement problem. For example, the front-loop of BMX cycling consists of a main phase (rotation), two first order supporting phases(pre-rotation and landing), and a second order supporting phase (drive-off). With regard to structure formation, the hierarchical alignment of BACs into groups (i.e., movement phases)is as well as the model of Rosenbaum (1983) interpreted as a tree-traversal model. Such a model consists of single nodes (BACs) which form the basic level of understanding. Single nodes connect to higher-level nodes describing certain parts of the movement problem. The next higher level connects these parts of the movement problem via a phase integration to the global movement problem. Thus, single BACs can be retrieved consciously from the memory, but the topology (i.e., the cognitive structure) of BACs not.

The described cognitive architecture of complex motor actions (Schack, 2004b; 2010) delivered insights in the structure formation of cognitive representations that solve complex movement problems. Global goals at the level of mental control (e.g., solving a movement problem) and related BACs at the level of mental representations are now directly connected to sensorial effects at the level of sensorimotor representation. This structure-formation process allows a direct communication with the environment. Thus, this model assumes that mental representations follow the principle of common coding (Prinz, 1990) between perception and action.

Up to now, BACs are the relevant representation unit at the level of mental representations, which describe the cognitive representation of complex motor actions. However, how are cognitive representation units organized at other movement-related complexity levels like manual actions, complex actions, and interactions? Assuming that representation units integrate sensory and goal-oriented feature dimensions, similar research methods should uncover them. To investigate such an assumption about the cognitive movement organization of mental control experiments need to be performed at all three movement-related complexity levels (i.e., manual actions, complex actions, and interactions).

The current thesis uses that approach of a cognitive architecture and connects it to different environmental settings in the fields of manual action, complex action, and interaction. Therefore, experiments are conducted that will expand the existing knowledge of mechanisms in the organization of representation units. If such a mechanism is present, it must be verifiable under all three movement-related complexity levels (i.e., manual actions, complex actions, and interactions). Therefore, the experiments try to locate Basic Movement Concepts (BMC) at the level of sensorimotor representation, Basic Action Concepts (BAC) at the level of mental representation, and Basic Interaction Concepts (BIC) at the level of mental control.

Research questions and hypotheses

Manual actions

In the daily life, humans are able to adapt to new environmental conditions and learn new relationships between sensory input and motor output. For example, a car driver has to register all perceptive inputs from his car in order to transfer adequate commands to his muscles, especially if he changes the car model (e.g., from a Chevrolet to a BMW). That example illustrates that, sensorimotor adaptation is a learning process, which is active when actual sensory consequences differ from expected sensory consequences of motor actions (Kelso, 1995). The question is which cognitive parameters influence the sensorimotor adaptation behavior? Numerous studies have addressed that phenomenon, called sensorimotor adaptation, in laboratory settings. Rest breaks in between trials, for instance, have a beneficial effect on the sensorimotor adaptation when they last at minimum five seconds. These rest breaks in between trials consolidate previously acquired sensorimotor recalibration rules (Bock, Thomas, & Grigorova, 2005). In addition, different adaptation tasks use similar already acquired recalibration rules. For example, a recalibration rule (e.g., visuomotor distortion of a clockwise rotation of 60°) delivers transfer effects from a pointing to a tracking task (Abeele & Bock, 2003). The described phenomena addresses an internal model, which possesses various properties, like gradual adjustability. Usually an increased visual distortion (e.g., 0°, 45°, 60°, and 90°) will lead to an increased error in adaptation behavior in a comparable period. However, the pre-exposure to a distortion similar to the recent distortion (e.g., from 60° rotation in the pre-adaptation task to 90° in the adaptation task) will lead to a smaller error. Thus, humans are able to adjust their behavior gradually (Abeele & Bock, 2001). These experiments aimed at the investigation of sensorimotor adaptation behavior to learn about a potential cognitive reference structures that might have an impact on adaptation behavior. The application of a pointing task (i.e., execution of pointing movements in certain directions) implied that cognitive representations of movement directions might have an impact on the performance. Studies investigating goal-oriented grasping behavior of rhesus monkeys (Georgopoulos, Kalaska, & Massey, 1981; Georgopoulos, Schwartz, & Kettner, 1986) delivered neurophysiologic evidence for the existence of representations movement directions. These authors monitored the population vector of activated motor cortical neurons during goal-oriented grasping movements. The observation verified the prediction of movement directions inferred from the activation of direction sensitive neurons. Thus, the actual movement vector of goal-oriented grasping movements lies within a 95% confidence interval cone around the population vector of activated neurons of the arm area. If there is neurophysiologic evidence for the existence of representations of movement directions, then there should also be a cognitive representation of movement directions accessible. Therefore, the aim of CHAPTER 2 and CHAPTER 3 is to determine the organizational structure of cognitive representations of movement directions in relation to individual's sensorimotor adaptation performance.

Moreover, the *optimal integration model* (van Beers, Wolpert, & Haggard, 2002) suggests a weighting of information from different input modalities (e.g., visual or proprioceptive input).For sensorimotor adaptations in depth (e.g., mirroring along the horizontal axis) participants would rely more on vision, as compared to sensorimotor adaptations in azimuth (e.g., mirroring along the sagittal axis) where participants rely more on proprioception. Such an adaptation behavior probably influences the cognitive representation of movement directions. Therefore, the measurement of the cognitive representation of movement directions was adjusted to visual (CHAPTER 2) and visual-proprioceptive stimuli (CHAPTER 3) in the experiments.

Complex actions

Different variables describe motor expertise (e.g., field of expertise, higher performance than usual, number of years of practice, etc.).

Different structures of a complex motor action established in the LTM determine motor expertise (Schack & Mechsner, 2006). Moreover, the direct matching hypotheses delivered evidence for a comparable neurophysiologic activation in the brain of rhesus monkeys during the execution and the observation of motor actions. This mechanism enables organisms to interpret other organisms' actions by mapping the observed actions onto existing representations (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). In general, the gaze behavior of humans is predictive, i.e., the gaze shifts to certain points of interest before the movement executing end-effector (e.g., the hand) reaches that location. Such a gaze behavior is observable, when humans execute a movement and when humans observe the movement execution. Thus, cognitive representations control the gaze behavior in both cases (i.e., movement observation and movement execution; Flanagan & Johansson, 2003). However, these finding do not distinguish motor and perceptual expertise. Therefore, a study investigated the action anticipation and motor resonance in elite basketball players (Aglioti, Cesari, Romani, & Urgesi, 2008). The task for the observers (basketball experts, novices, and watchers) was to state within a temporal occlusion paradigm whether a player scores, or not, in basketball free throws. The findings expose differences between groups observed for movement phases even before the ball left the hand, suggesting that experts can interpret body kinematics more accurately and more easily as compared to novices. Experts are able to predict other player's behavior ahead of their realization, because they possess a functionally organized cognitive representation structure. It seems that experts use their representation of motor actions and the corresponding sensorial movement feedback (Aglioti, Cesari, Romani, & Urgesi, 2008). Thus, elaborated cognitive representation structures are an indicator for motor expertise. However, how do experts process movements, which are not identical but similar to their motor expertise?

Neurophysiologic evidence delivered that a network of activations in the motor cortex is involved in execution and observation of complex motor actions. This activation is stronger when humans possess a specific cognitive representation of that motor action. The brain activation is less strong if similar movements (i.e., matched with regard to the kinematics of a movement) from different fields of expertise (i.e., classical ballet and Capoeira) are perceived. This finding signifies the transfer of visual inputs onto specific motor skills of the observer. Thus, parietal and premotor areas in the human brain do not just simply react on the kinematics of a movement (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005). CHAPTER4 has two goals. (1) The study delivers insights in the organization of cognitive representation of experts and novices for the instep kick in soccer. (2) The goal is to investigate whether, or not, the cognitive representation is different for the comparable movements executed by a human and a humanoid robot. If humans possess an expertise for a specific motor action, the transfer onto a new and unknown motor system (i.e., humanoid robot) seems plausible.

Interactions

Interaction-relevant cognitive units stored in the LTM are objects of research at the level of cognitive representations in CHAPTER 5. Therefore, the cognitive representation of team-specific tactics in soccer is investigated. Usually, a post-hoc video analysis describes team specific tactics by focusing on different tactical performance indicators and latent variables (Garganta, 2009). This kind of research grounds on the decomposition of the game, the detection of static patterns, and the analysis of discrete variables that inform about some characteristics of a soccer match. It seems plausible that higher order cognitive parameters of movement organization are an integral component in the realization of stipulated tactics. Compared to technical and physical performance parameters the research regarding tactics in sport games and the analysis of the relevant cognitive variables stands right at the beginning of a broader development. The current thesis do not follow this reductionist approach. Instead, it studies aspects of the complexity of interactions (i.e., team-specific tactics) in soccer. Appropriate cognitive reference structures of complex motor actions (i.e. BACs) should provide a basis for action control in skilled voluntary executed movements (Schack & Mechsner, 2006). These BACs are activated in movement execution based on tactical decisions.

The tactical understanding is of central relevance for the playing competence of each player, especially at a higher expertise level (Höner, 2005). Social interactions in sports (like tactical decisions on the soccer pitch) base on the perception of the intentions of other players (Nitsch, 2004) and the useful classification of perceived interactions. Therefore, soccer players must be able to anticipate opponents and teammates intentions in advance to process perceived interactions (Meinel & Schnabel, 2007). Cognitive skills and abilities of an individual influence the cognitive processing of relevant sensory information. Adequate motor processes rely on the results of the cognitive processing (Bosbach, Prinz, & Kerzel, 2004). Thus, the selection of action-relevant perceptual features influences the choice for an adequate tactical behavior. Numerous studies investigated the tactical behavior of players. For example, soccer experts are better in prioritizing and evaluating a possible tactical behavior. Experts are better able to make exact judgments about possible passing options as compared to novices when both groups judge identical match situations (Ward & Williams, 2003). Novices in soccer showed a greater recall error as experts when players' positions on the pitch needed to be recognized (Williams, Davids, Burwitz, Williams, 1993). Additionally, the investigation of explicable tactical knowledge of soccer experts and novices showed advantages for the soccer experts. Experts were able to state verbally more relevant information in the description of a scene as compared to novices. That helped the experts to make appropriate task-specific judgments (den Hartigh, van der Steen, de Meij, van Yperen, & Gernigon, 2014; Roca, Ford, McRobert, & Williams, 2011). Thus, it can be assumed that tactic-specific knowledge is organized in conceptual units in the human LTM as tactical skills (Hodges, Huys, & Starkes, 2007; McPherson & Kernodle, 2003). The main purpose of the CHAPTER5 is to identify cognitive representations of team-specific tactics in soccer. If soccer experts possess functionally aligned cognitive representations of team-specific tactics in soccer, it will have an impact on the cognitive processing of identical match situations. Two additional methods (i.e., a reaction time paradigm and a measurement of gaze behavior) test the hypothesis regarding the decision-making process in team-specific tactics.

References

Abeele, S., & Bock, O. (2001). Sensorimotor adaptation to rotated visual input: Different mechanisms for small versus large rotations. *Experimental Brain Research, 140*(4), 407-410.

Abeele, S., & Bock, O. (2003). Transfer of sensorimotor adaptation between different movement categories. *Experimental Brain Research, 148*(1), 128-132.

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience, 11*(9), 1109-1116.

Ashby, F. G., & Lee, W. W. (1993). Perceptual variability as a fundamental axiom of perceptual science. In S. C. Masin (Ed.), *Foundations of Perceptual Theory* (pp. 369-399). Amsterdam: North Holland.

Ashby, F. G., &Ell, S. W. (2001). The neurobiology of human category learning. *Trends in Cognitive Science, 5*(5), 204-210.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Bernstein, N. A. (1971). Bewegungskontrolle (transl. Motor Control). In T. Kussmann & H. Kölling (Eds.), *Biologie und Verhalten* (pp. 146-171). Bern: Huber.

Bläsing, B., Tenenbaum, G., & Schack, T. (2009). The cognitive structure of movements in classical dance. *Psychology of Sport and Exercise, 10*(3), 350-360.

Bock, O. (2001). Mechanismen der sensomotorischen Adaptation beim Menschen (transl. Mechanisms of human sensorimotor adaptation). *Deutsche Zeitschrift für Sportmedizin, 52*(12), 338-342.

Bock, O., & Burghoff, M. (1997). Visuo-motor adaptation: Evidence for a distributed amplitude control system. *Behavioral Brain Research, 89*(1-2), 267-273.

Bock, O., & Girgenrath, M. (2006). Relationship between sensorimotor adaptation and cognitive functions in younger and older subjects. *Experimental Brain Research, 169*(3), 400-406.

Bock, O., Schneider, S., & Bloomberg, J. (2001). Conditions for interference versus facilitation during sequential sensorimotor adaptation. *Experimental Brain Research, 138*(3), 359-365.

Bock, O., Thomas, M., & Grigorova, V. (2005). The effect of rest breaks on human sensorimotor adaptation. *Experimental Brain Research, 163*(2), 258-260.

Bosbach, S., Prinz, W., & Kerzel, D. (2004). A Simon Effect With Stationary Moving Stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 30*(1), 39-55.

Braun, S. M., Beurskens, A. J., Schack, T., Marcellis, R. G., Oti, K. C., Schols, J. M., et al. (2007). Is it possible to use the Structural Dimension Analysis of Motor Memory (SDA-M) to investigate representations of motor actions in stroke patients? *Clinical Rehabilitation, 21*(9), 822-832.

Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex, 15*(8), 1243-1249.

Calvo-Merino, B., Grezes, J., Glaser, D. E., Passingham, R. E., & Haggard, P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. *Current Biology, 16*(22), 1905-1910.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology, 4*(1), 55-81.

Clark, A. (1998). *Being There: Putting Brain, Body, and World Together Again*. Cambridge: MIT Press.

Creem-Regehr, S. H. (2009). Sensory-motor and cognitive functions of the human posterior parietal cortex involved in manual actions. *Neurobiology of Learning and Memory, 91*, 166-171.

Cross, E. S., Hamilton, A. F. d. C., & Grafton, S. T. (2006). Building a motor simulation de novo: Observation of dance by dancers. *NeuroImage, 31*(3), 1257-1267.

de Groot, A. D. (1978/2008). *Thought and Choice in Chess*. The Hague: Mouton Publishers.

den Hartigh, R. J. R., van der Steen, S., de Meij, M., van Yperen, N. W., & Gernigon, C. (2014). Characterising expert representations during real-time action: A Skill Theory application to soccer. *Journal of Cognitive Psychology, 26*(7).doi:10.1080/20445911.2014.955028

Egan, F. (2012). Representationalism. In E. Margolis, R. Samuels & S. P. Stich (Eds.), *The Oxford Handbook of Philosophy of Cognitive Science*. Oxford: Oxford University Press.

Eimas, P. D. (1995). Categorization in early infancy and the continuity of development. In J. Mehler & S. Franck (Eds.), *Cognition on Cognition* (pp. 289-300). Cambridge: MIT Press.

Eversheim, U., & Bock, O. (2001). Evidence for processing stages in skill acquisition: A dual-task study. *Learning & Memory, 8*(4), 183-189.

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. *Nature, 424*(6950), 769-771.

Flanagan, J. R., Nakano, E., Imamizu, H., Osu, R., Yoshioka, T., & Kawato, M. (1999). Composition and decomposition of internal models in motor learning under altered kinematic and dynamic environments. *The Journal of Neuroscience, 19*(20).

Fodor, J. A. (1987). *Psychosemantics: The problem of meaning in the philosophy of mind*. Oxford: MIT Press.

Fodor, J. A., & Pylyshyn, Z. W. (1988). Connectionism and cognitive architecture: a critical analysis. *Cognition, 28*(1-2), 3-71

Gallese, V. (2003). A neuroscientific grasp of concepts: from control to representation. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358*(1435), 1231-1240.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*(2), 593-609.

Garganta, J. (2009). Trends of tactical performance analysis in team sports: bridging the gap between research, training and competition. *Revista Portuguesa de Ciências do Desporto, 9*(1), 81-89.

Georgopoulos, A. P., Kalaska, J. F., & Massey, J. T. (1981). Spatial trajectories and reaction-times of aimed movements - effects of practice, uncertainty, and change in target location. *Journal of Neurophysiology, 46*(4), 725-743.

Georgopoulos, A. P., Schwartz, A. B., & Kettner, R. E. (1986). Neuronal population coding of movement direction. *Science, 233*(4771), 1416-1419.

Gibson, J. (1966). *The Senses Considered as Perceptual Systems*. Oxford: Houghton Mifflin.

Gibson, J. (1979). *The Ecological Approach to Visual Perception*. Oxford: Houghton Mifflin.

Gobet, F., & Simon, H. A. (2000). Five seconds or sixty? Presentation time in expert memory. *Cognitive Science, 24*(4), 651-682.

Göhner, U. (1979). *Bewegungsanalyse im Sport (transl. Movement analysis in sports)*. Schorndorf: Hofmann.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41*(2), 301-307.

Herbart, J. F. (1825). *Psychologie als Wissenschaft, neu gegründet auf Erfahrung, Metaphysik und Mathematik (Vol. 2) (transl. Psychology as Science)*. Königsberg: Unzer.

Hodges, N. J., Huys, R., & Starkes, J. L. (2007). Methodological review and evaluation of research in expert performance in sport. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of Sport Psychology*. Hoboken (NJ): John Wiley & Sons.

Hoffmann, J. (1986). *Die Welt der Begriffe (transl. The world of concepts)*. Berlin: Verlag der Wissenschaften.

Hoffmann, J. (1998). Kognition im Dienste der Handlungssteuerung (transl. Cognition at service of motor control). *Psychologische Rundschau, 49*(1), 21-30.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5), 849 - 878.

Höner, O. (2005). *Entscheidungshandeln im Sportspiel Fußball – Eine Analyse im Lichte der Rubikontheorie (transl. Decision-making in sport game soccer - An analysis in terms of Rubicon-Theory)*. Schorndorf: Hofmann.

James, W. (1890). *The principles of psychology* (Vol. 1). New York: Holt.

Janelle, C. M., & Hillman, C. H. (2003). Expert performance in sport: Current perspectives and critical issues. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert Performance in Sports - Advances in Research on Sport Expertise* (pp. 19-47). Champaign (IL): Human Kinetics.

Jeannerod, M. (1997). *The cognitive neuroscience of action*. Malden: Blackwell Publishing.

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *Neuroimage, 14*(1), 103-109.

Kandel, E. R., Schwartz, J. H., Jesell, T. M., Siegelbaum, S. A., & Hudspeth, A. J. (2012). *Principles of Neuroscience* (5th ed.). New York: McGraw-Hill.

Kelso, J. A. S. (1995). *Dynamic patterns - The self-organization of brain and behavior*. Cambridge: MIT Press.

Klix, F. (1971). *Information und Verhalten (transl. Information and Behavior)*. Bern: Huber.

Koch, I., Keller, P.,& Prinz, W. (2011). The ideomotor approach to action control: Implications for skilled performance. *International Journal of Sport and Exercise Psychology, 2*(4), 362-375.

Kohonen, T. (1997). *Self-organizing Maps*. Berlin: Springer.

Konczak, J. (1996). Benutzt das Gehirn "motorische Programme" zur Steuerung von Bewegungen? (transl. Does the brain use motor programs for movement coordination?). In R. Daugs & K. Blischke (Eds.), *Kognition und Motorik* (pp. 41-58). Hamburg: Czwalina.

Konczak, J. (2002). Internal motor models: A conceptual framework for motor control, learning, and development. *Journal of Sport & Exercise Psychology, 24*(Supplement), 7-8.

Krakauer, J. W., Ghilardi, M. F., & Ghez, C. (1999). Independent learning of internal models for kinematic and dynamic control of reaching. *Nature Neuroscience, 2*(11), 1026-1031.

Krause, A. F., Bläsing, B., & Schack, T. (2009). Modellierung kognitiver Strukturen mit hierarchischen selbstorganisierenden Karten (transl. Modelling of cognitive structures by self-organizing maps). In S. D. Baumgärtner, F. Hänsel & J. Wiemeyer (Eds.), *Informations- und Kommunikationstechnologien in der Sportmotorik* (pp. 171-173). Hamburg: TK.

Lotze, R. H. (1846). Seele und Seelenleben (transl. Mind and Inner-life). In R. Wagner (Ed.), *Handwörterbuch der Physiologie* (transl. Dictionary of Physiology). Braunschweig: Vieweg.

Lotze, R. H. (1852). *Medicinische Psychologie oder Physiologie der Seele (transl. Medical psychology or physiology of the mind)*. Leipzig: Weidmann.

MacKay, D. G. (1985). A theory of representation, organization, and timing of action with implications for sequencing disorder. In E. A. Roy (Ed.), *Advances in Psychology: Neuropsychological Studies of Apraxia* (Vol. 23, pp. 267-308). Amsterdam: Elsevier.

Markman, A. B., & Dietrich, E. (2000a). Extending the classical view of representation. *Trends in Cognitive Science, 4*(12), 470-475.

Markman, A. B., & Dietrich, E. (2000b). In defense of representation. *Cognitive Psychology, 40*(2), 138-171.

Martin, A., Wiggs, C. L., Ungerleider, L. G., & Haxby, j. V. (1996). Neural correlates of category-specific knowledge. *Nature, 379*(6566), 649-652.

Mazzoni, P., & Krakauer, J. W. (2006). An implicit plan overrides an explicit strategy during visuomotor adaptation. *The Journal of Neuroscience, 26*(14), 3642-3645.

McPherson, S. L., & Kernodle, M. W. (2003). Tactics, the neglected attribute of expertise. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert Performance in Sports - Advances on Research in Sport Expertise*. Champaign (Il): Human Kinetics.

Mechsner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature, 414*(6859), 69-73.

Meinel, K., & Schnabel, G. (2007). *Bewegungslehre Sportmotorik (transl. Kinematics Motor Action)*. Aachen: Meyer & Meyer.

Mervis, C. B., & Rosch, E. (1981). Categorization of natural objects. *Annual Review of Psychology, 32*, 89-115.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: an expanded sourcebook.* Thousand Oaks: Sage Publications.

Munzert, J. (1989). *Flexibilität des Handelns: theoretische Überlegungen und experimentelle Untersuchungen zum Konzept des Motorikschemas (transl. Flexibility of Acting)*. Köln: bps.

Munzert, J. (1992). Motorik-Repräsentation, Bewegungswissen und Bewegungshandeln (transl. Motor representation, movement knowledge, and movement execution). *Sportwissenschaft, 22*(3), 344-356.

Munzert, J. (1995). Expertise im Sport (transl. Expertise in Sport). *Psychologie und Sport, 2*, 122-131.

Munzert, J. (1997). *Sprache und Bewegungsteuerung (transl. Language and motor control)*. Schorndorf: Hofmann.

Müsseler, J., Aschersleben, G., & Prinz, W. (1996). Die Steuerung von Handlungen (transl. The control of actions). In G. Roth & W. Prinz (Eds.), *Kopf-Arbeit: Gehirnfunktionen und kognitive Leistungen* (pp. 309-358). Heidelberg: Spektrum.

Nitsch, J. R. (2000). Handlungstheoretische Grundlagen der Sportpsychologie (transl. Action-theory basics of sportpsychology). In H. Gabler, J. R. Nitsch & R. Singer (Eds.), *Einführung in die Sportpsychologie. Teil 1: Grundlagen* (Vol. 2, pp. 43-164). Schorndorf: Hofmann.

Nitsch, J. R. (2004). Die handlungstheoretische Perspektive: ein Rahmenkonzept für die sportpsychologische Forschung und Intervention (transl. The action-oriented perspective: A framework for research in sport psychology and intervention). *Zeitschrift für Sportpsychologie, 11*(1), 10-23.

Petersen, M. J., & Graham, S. E. (1974). Visual detection and visual imagery. *Journal of Experimental Psychology, 103*(3), 509-514.

Pezzulo, G., Hoffmann, J., & Falcone, R. (2007). Anticipation and anticipatory behavior. *Cognitive Processing, 8*(2), 67-70.

Pfeifer, R., & Scheier, C. (1999). *Understanding intelligence*. Cambridge: MIT Press.

Piaget, J. (1952). *The Origins of Intelligence in Children*. New York: Norton & Co.

Pinker, S. (1997). *How the mind works*. New York: W.W. Norton & Company.

Prinz, W. (1983). *Wahrnehmung und Tätigkeitssteuerung (transl. Perception and Motor Control)*. Berlin: Springer.

Prinz, W. (1987). Ideo-motor action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on Perception and Action* (pp. 47-76). Hillsdale: Lawrence Erlbaum Associates.

Prinz, W. (1990). A common coding approach to perception and action. In W. Prinz & O. Neumann (Eds.), *Relationships between perception and action, Current approaches* (pp. 167-201). Berlin: Springer.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*(2), 129-154.

Prinz, W. (2000). Kognitionspsychologische Handlungsforschung (transl. Cognitive and psychological research of human actions). *Zeitschrift für Psychologie, 208*(1-2), 32-54.

Prinz, W. (2005). An ideomotor approach to imitation. In S. Hurley & N. Chater (Eds.), *Perspectives on imitation: From neuroscience to social science - Volume 1: Mechanisms of imitation and imitation in animals*. Cambridge: MIT Press.

Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neuroscience, 21*(5), 188-194.

Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M. (2011). Identifying the processes underpinning anticipation and decision-making in a dynamic time-constrained task. *Cognitive Processing, 12*(3), 301-310.

Rosch, E. (1973). Natural categories. *Cognitive Psychology, 4*(3), 328-350.

Rosch, E. (1975). The nature of mental codes for color categories. *Journal of Experimental Psychology, 1*(4), 303-322.

Rosch, E. (1978). Principles of categorization. In E. Rosch & B. B. LLoyd (Eds.), *Cognition and Categorization*. Hillsdale: Lawrence Erlbaum Associates.

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects and natural categories. *Cognitive Psychology, 8*, 382-439.

Rosenbaum, D. E. (1983). The movement precuing technique: Assumptions, applications, and extensions. In R. A. Magill (Ed.), *Advances in Psychology: Memory and Control of Action* (Vol. 12, pp. 231-274). North-Holland: Elsevier.

Schack, T. (2002). *Die kognitive Architektur komplexer Bewegungen - modelltheoretische und experimentelle Zugänge zu einer integrativen Bewegungswissenschaft (transl. The Cognitive Architecture of Complex Motor Actions)*. [Habilitation treatise]. Cologne: German Sports University.

Schack, T. (2004a). Knowledge and performance in action. *Journal of Knowledge Management, 8*(4), 38-53.

Schack, T. (2004b). The cognitive architecture of complex movement. *International Journal of Sport and Exercise Psychology, 2*(4), 403-438.

Schack, T. (2010). *Die kognitive Architektur menschlicher Bewegungen – Innovative Zugänge für Psychologie, Sportwissenschaft und Robotik (transl. The cognitive architecture of human movements - innovative approaches to psychology, sport science, and robotic)*. Aachen: Meyer & Meyer.

Schack, T., & Hackfort, D. (2007). Action-theory approach to applied sport psychology. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of Sport Psychology* (3rd ed., pp. 332-351). Hoboken, NJ: John Wiley & Sons.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. *Neuroscience Letters, 391*(3), 77-81.

Schack, T., & Ritter, H. (2009). The cognitive nature of action - Functional links between cognitive psychology, movement science, and robotics. *Progress in Brain Research, 174*, 231-250.

Schack, T., Stöckel, T., & Weigelt, M. (2008). Kognition und Emotion - Bausteine einer Bewegungsarchitektur (transl. Cognition and emotion - Building blocks of a movement architecture). *Leipziger Sportwissenschaftliche Beiträge, 49*(1), 104-124.

Scheele, B., & Groeben, N. (1988). *Dialog-Konsens-Methoden zur Rekonstruktion subjektiver Theorien (transl. Dialog-Consensus-Method for the reconstruction of subjective theories)*. Tübingen: Francke.

Scheerer, E. (1984). Motor theories of cognitive structure. In W. Prinz & A. F. Sanders (Eds.), *Cognition and motor processes*. Berlin: Springer.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*(4), 225-260.

Schmidt, R. A., & Lee, T. D. (1998). *Motor control and learning: A behavioral emphasis*. Champaign: Human Kinetics.

Schütz-Bosbach, S., & Prinz, W. (2007). Prospective coding in event representation. *Cognitive Processing, 8*(2), 93-102.

Shadmehr, R., & Holcomb, H. H. (1997). Neural correlates of motor memory consolidation. *Science, 277*, 821-825.

Shadmehr, R., & Moussavi, Z. M. K. (2000). Spatial generalization from learning dynamics of reaching movements. *The Journal of Neuroscience, 20*(20), 7807-7815.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review, 91*(4), 417-447.Shiffrin, R. M. (1970). Forgetting: Trace erosion or retrieval failure? *Science, 168*(3939), 1601-1603.

Smith, E. E., Balzano, G. J., & Walker, J. H. (1978). Nominal, perceptual, and semantic codes in picture categorization. In J. Cotton & R. Klatzky (Eds.), *Semantic factors in cognition*. Hillsdale: Lawrence Erlbaum Associates.

Sommerville, J. A., & Decety, J. (2006). Weaving the fabric of social interaction: Articulating developmental psychology and cognitive neuroscience in the domain of motor cognition. *Psychonomic Bulletin & Review, 13*(2), 179-200.

Starkes, J. L., & Allard, F. (1993). *Cognitive Issues in Motor Expertise*. Amsterdam: North-Holland.

Starkes, J. L., & Ericsson, K. A. (2003). *Expert Performance in Sports: Advances in Research on Sport Expertise*. Champaign: Human Kinetics.

Starkes, J. L., Helsen, W. F., & Jack, R. (2001). Expert performance in sport and dance. In R. N. Singer, H. A. Hausenblas & C. M.

Janelle (Eds.), *Handbook of Sport Psychology* (pp. 174-201). New York: Wiley.

Tani, J., Itob, M., & Sugita, Y. (2004). Self-organization of distributedly represented multiple behavior schemata in a mirror system: reviews of robot experiments using RNNPB. *Neural Networks, 17*(8-9), 1273-1289.

Taylor, J. A., & Thoroughman, K. A. (2008). Motor adaptation scaled by the difficulty of a secondary cognitive task. *PLoS ONE, 3*(6), 1-11.

Thomas, K. T., & Thomas, J. R. (1994). Developing expertise in sport: The relation of knowledge and performance. *International Journal of Sport Psychology, 25*(3), 295-312.

Tversky, A. (1977). Features of similarity. *Psychological Review, 84*, 327-352.

van Beers, R. J., Wolpert, D. M., & Haggard, P. (2002). When feeling is more important than seeing in sensorimotor adaptation. *Current Biology, 12*(10), 834-837.

Volkmann, A. W. (1846). Sehen. In R. Wagner (Ed.), *Handwörterbuch der Physiologie (transl. Dictionary of Physiology)* (pp. 264 - 351). Braunschweig: Vieweg.

Vygotsky, L. S. (1934/1962). *Thought and Language (Original work published 1934)*. Cambridge: MIT Press.

Ward, P., & Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: The multidimensional nature of expert performance. *Journal of Sport & Exercise Psychology, 25*(1), 93-111.

Weigelt, M., Ahlmeyer, T., Lex, H., & Schack, T. (2011). The cognitive representation of a throwing technique in judo experts - Technological ways for individual skill diagnostics in high-performance sports. *Psychology of Sport and Exercise, 12*(3), 231 - 235.

Westerholz, J., Schack, T., & Koester, D. (2013). Event-related brain potentials for goal-related power grips. *PLoS ONE, 8*(7), e68501.

Westerholz, J., Schack, T., Schütz, C., & Koester, D. (2014). Habitual vs non-habitual manual actions: An ERP study on overt movement execution. *PLoS ONE, 9*(4), e93116.

Williams, A. M., Davids, K., Burwitz, L., & Williams, J. (1993). Cognitive knowledge and soccer performance. *Perceptual and Motor Skills, 76*(2), 579-593.

Wollesen, B., Lex, H., & Mattes, K. (2012). BASE als Programm zur Prävention von (Rücken-)Beschwerden in der betrieblichen Gesundheitsförderung (transl. BASE a program for the prevention of backache in industrial health promotion). *Gruppendynamik und Organisationsberatung, 43*, 389-411.

Wolpert, D. M., Doya, K., & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358*(1431), 593-602.

Wundt, W. (1898). Zur Theorie der räumlichen Gesichtswahrnehmung (transl. Theory of spatial facial perception). *Philosophische Studien, 14*, 1-118.

Zacks, J. M., & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin, 127*(1), 3-21.

Zacks, J. M., Tversky, B., & Iyer, G. (2001). Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology, 130*(1), 29-58.

Representation in Manual Actions – I

CHAPTER 2

Abstract The current study investigated the effects of cognitive representations of movement directions on sensorimotor adaptation performance. Adaptation performance was measured via a pointing experiment in which participants were provided with visual feedback that was distorted along the midsagittal plane (i.e., left-right reversal). Performance was analyzed relative to participants' individual adaptation gains and three groups were subsequently defined (i.e. skilled, average, and poor adapters). The group separation was kept for the Cognitive Measurement of Represented Directions (C-MRD), which was used to analyze participants' cognitive representation of movement directions. The results showed that skilled adapters, in contrast to poor adapters, possess a global representation of movement directions aligned to the cardinal axes. The cognitive representation structure hence supports the sensorimotor adaptation performance.

This chapter is a revised version of Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2014). The functional role of cognitive frameworks on visuomotor adaptation performance. Journal of Motor Behavior, *46*(6), 389-396.

Introduction

Sensorimotor adaptation can be characterized as a learning process, which is driven by the formation of new links between motor output and sensory feedback (Ferrel, Bard, & Fleury, 2001). The current scientific research on the cognitive principles responsible for sensorimotor adaptation focuses on the modification characteristics of an internal model as one kind of internal representation of environmental properties (Wolpert, Ghahramani, & Jordan, 1995). Modifications of an existing internal model towards visual disturbances can be stored in memory, something that, among other things, can be seen in a reduced error when adapting to a similar disturbance for the second time (Abeele & Bock, 2001). Previous research demonstrated that such a modified internal model persists over time and can be retained for more than a month (Bock, Schneider, & Bloomberg, 2001).

To overcome the initial performance disruption at the beginning of distorted trials, other processes than transformations of the internal model must be activated (Bock, 2005; Redding & Wallace, 1996). These processes can be described as a gradual adaptation to new environmental conditions as strategic control, which relies on cognitive representations (Mazzoni & Krakauer, 2006). Evidence for this assumption was previously provided by a study that investigated the adaptation performance of a deafferent patient (i.e., a patient with a neurological disorder blocking sensory feedback from the neck on downwards). A further decrease in the adaptation performance was found when the patient was engaged in an additional cognitive task (e.g., counting task), compared to a healthy control group (Ingram, van Donkelaar, Cole, Vercher, Gauthier, & Miall, 2000). This finding provided evidence that cognitive processes are involved in sensorimotor adaptation, but it remains unclear, however, which strategic cognitive processes are responsible for the sensorimotor adaptation performance.

Within the classical research paradigm of goal-directed pointing experiments, the cognitive representation of movement directions has previously been found as one functional indicator to measure sensorimotor adaptation performance (Lex, Weigelt, Knoblauch, & Schack, 2012). Lex and colleagues (2012) provided evidence for the existence and specifics of cognitive representations of movements directions, when the movement directions are presented in a proprioceptive-visual mode. According to their results, differences in sensorimotor adaptation behavior between different groups of participants are caused by different cognitive representations of movement directions (i.e., global and local representations). Global representations of movement directions are aligned to the cardinal axes in the sagittal and horizontal plane. In contrast, local representations of movement directions are aligned to neighboring movement directions (i.e., 30° apart from each other). Global cognitive representations of movement directions have been found to lead to a better adaptation performance in a task, in which visual feedback was distorted via a left-right reversal (i.e., a mirroring along the sagittal axis). The termini global and local are used herein with emphasis to the organization of corresponding movement directions.

Sensory motor adaptation performance has also been shown to be influenced by different sensory input modalities (e.g., visual, kinesthetic, or proprioceptive feedback) in accordance with the adjusted distortion (van Beers, Wolpert, & Haggard, 2002). For example, in a sensorimotor adaptation towards a distortion of the visual feedback in terms of a sagittal displacement humans tend to rely more on proprioceptive movement feedback. Whereas, during the adaptation towards a distortion in terms of a horizontal displacement humans rely more on visual movement feedback.

The aim of the present study was to investigate sensorimotor adaptation performance with a distortion of the visual feedback in terms of a left-right reversal (i.e., horizontal displacement), and to measure the corresponding cognitive representations of movement directions when presented only in a visual mode. Thus, the study builds on the earlier investigation of Lex et al. (2012) in which the movement directions were presented in a proprioceptive-visual mode and aimed to examine the functional relationship between the cognitive representation and the adaptation behavior to visually presented movement directions.

Methods

Two experiments were conducted to investigate the functional relationship between cognitive representations of movement directions and subsequent sensorimotor adaptation behavior. Experiment 1 measured the cognitive representation of movement directions under the visual input modality. Experiment 2 assessed sensorimotor adaptation using a pointing task similar to the one previously used by Bock and Girgenrath (2006) integrating a different distortion of the visual feedback.

Participants

Forty-seven adults (mean age = 25.4 years, SD = 2.8, 24 females) participated in the current study, with the majority of them being students at Bielefeld University. All participants declared themselves as right-handed, they were naïve to the purpose of the experiment, and had normal or corrected-to-normal vision. The experiment consisted of a single session (starting with the measurement of the cognitive representation of movement directions), and experimental procedures were conducted in accordance with the 1964 Declaration of Helsinki. Participants signed an informed consent form prior to the experiment and received course credit for their research participation. All data was collected in a single session starting with the data acquisition of the measurement of cognitive representation of movement directions.

Sensorimotor adaptation task

Performance in the sensorimotor adaptation task was measured using a standard pointing experiment (Bock 2005; Miall, Jenkinson, & Kulkarni, 2004). Participants were asked to execute center-out movements towards eight randomly appearing targets on a digitizer tablet. Movements were always performed from the center to the periphery of the screen and participants' hand locations on the digitizer tablet were displayed via a red cursor on the screen. After baseline recordings, visual feedback was distorted in terms of a left-right reversal in order to manipulate the normal relationship between sensory input and motor output.

Apparatus & Task

The apparatus and task used in the current experiment were identical to the sensorimotor adaptation task of Lex and colleagues (2012). Participants were seated in front of a monitor facing downwards. The screen was visible through a tilted mirror which prevented vision of the own hands. Participants` right hand executed center-out movements from a center position to eight peripheral, equidistant target positions, randomly appearing on a digitizer tablet. To provide participants with real-time visual feedback of their hand movements, the hand position was displayed via a red cursor cross (8mm in length and width) on the screen (similar to Miall, Jenkinson, & Kulkarni, 2004). Participants were asked to perform the movements with their right hand using an electronic pen, while the left hand was positioned and kept still beside the digitizer tablet. Movements were performed in episodes of 30 s, with a five seconds rest in between episodes (Bock, 2005; Bock & Girgenrath, 2006). The experiment started with three familiarization episodes, which were followed by two undistorted baseline conditions consisting of five episodes each. Baseline condition 1 (BL1) recorded participants' performance with veridical visual feedback of their movements. Baseline condition 2 (BL2) recorded the same movements than BL1, but without real-time visual feedback of the actual hand position. Instead, feedback of the cursor position was only provided when the cursor was within an arc radius of 10 mm around the center position of the screen to ensure participants were able to return to the starting position. The two BL conditions were followed by an adaptation phase (AP), in which participants were asked to perform the same movement task, but were presented with visual feedback that was distorted via a left-right reversal (i.e., mirrored along the midsagittal plane). The AP consisted of 30 episodes to ensure there was enough time to initiate a sensorimotor adaptation process. Subsequent to the AP participants were offered a 5 minute break in which they were allowed to move around and relax. They continued with five episodes in the phase of persistence (PP) under distorted condition, but without real-time visual feedback of the movements.

Data analysis

An initial angular error (IAE) was measured to determine participants' pointing performance. The IAE was computed between the direct target direction and initial hand direction for each pointing movement. The direct target direction was defined by the hand position at movement onset (i.e., center position) and the target location. The initial hand direction in contrast was defined by the hand position at movement onset (i.e., center position) and the hand position at first peak velocity with a minimum velocity of 30 mm/s. The minimum velocity threshold at movement onset was defined to ensure that initial small corrective adjustments (i.e., directly around the center position) were not considered within data analysis. Overall, the IAE measure is largely unaffected by feedback-based corrective adjustments that occur during later stages of the pointing movement, in which participants slow down their movements and perform a winding path towards the target to ensure for successive movement performance. The mean IAE was calculated for all pointing movements within each episode. The mean adaptation performance of each episode was averaged into blocks of five episodes to judge participants' pointing performance (Bock & Girgenrath, 2006). Therefore, the blocks measuring pointing performance were constituted as BL1, BL2, AP1 to AP6, and PP representing the mean pointing performance of five episodes each. An analysis of variance (ANOVA) with repeated measures and a simple contrast analysis were conducted to examine differences within the adaptation phase. Baseline performances were examined by a two-tailed t-test.

Cognitive representation of movement directions

The representation of movement directions was measured using the Cognitive Measurement of Represented Directions (C-MRD), an experimental set-up used by Lex and colleagues (2012), and based on the methodological background of the Structural Dimensional Analysis of Motor Representations (SDA-M; Schack & Mechsner, 2006).

Apparatus and task

The C-MRD was performed at the same table as the sensorimotor task. A standard monitor was placed in front of the participants used to provide normal vision on the screen. Following the sensorimotor adaptation task, we used animated red fading movement dots (with a center-out movement direction) to measure cognitive representations of movement directions. The moving dots were depicted as animated gif-files on the computer screen (see Figure 2.1), and moved into twelve different directions, spread evenly on a full circle every 30°. One of the twelve movement directions was presented in the upper part of the (horizontally split) screen in an anchoring position, and the remaining eleven movement conditions were successively and randomly presented in the lower part of the screen in a signifier position. The movement direction in the anchoring position remained repetitive on the screen, until it was compared with every other movement direction. Subsequent to that, the next movement direction was displayed as well in the anchoring position, and compared with the remaining eleven movement directions. The procedure was repeated until each movement direction had been presented once in the anchoring position. Twelve movement directions were compared with each other, thus asking participants to make twelve times eleven decisions in total, as the anchoring position was predefined as most similar to itself.

The task for the participants was to compare the movement direction in the anchoring position with that in the signifier position concerning their similarity. More specifically participants were asked to decide whether the two presented movement directions seemed similar to them. Participants were instructed to make their decisions spontaneously, which was facilitated through a singular stimuli presentation, but no given time restrictions. Decisions were made by either pressing a plus button (similarity) on the left or a minus button (no similarity) on the right side of the screen. Participants' judgment was entirely based on a self-defined similarity criterion, and made with regard to their own representation of movement directions.

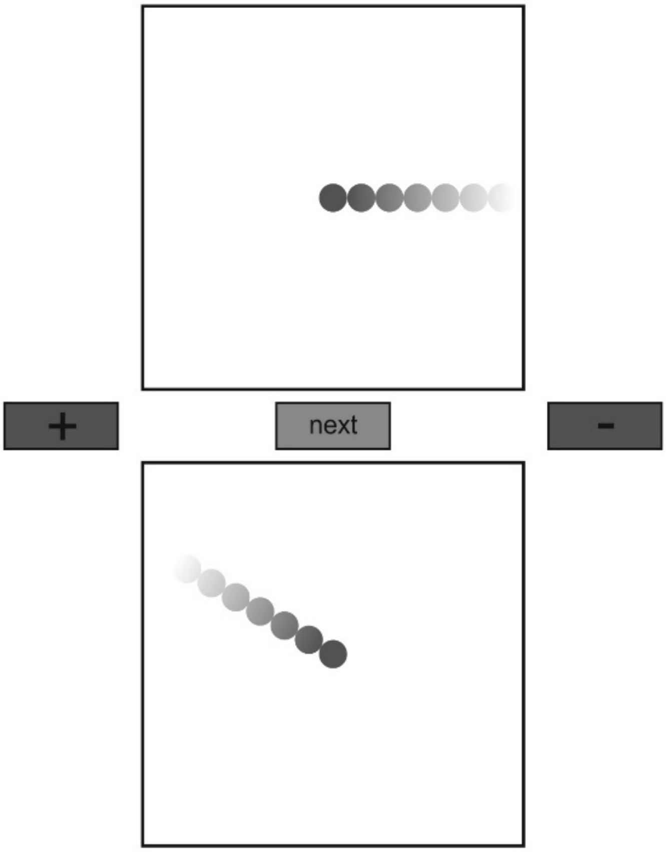

Figure 2.1 C-MRD reveals data of cognitive representation of movement directions. When the splitting procedure started, the dot (colored in red) in the upper screen (anchoring position) moved into one movement direction (e.g. direction 4 = 90° straight to the right). After this one faded out, the dot in the lower screen (signifier position) moved into one of the other residual eleven movement directions (e.g. direction 11 = 300° to the upper left). When the participants decided for similarity they pressed the plus button (on the left), and for dissimilarity the minus button (on the right). The next movement direction appeared immediately the decisions. When the movement direction in anchoring position was compared with every other direction, the next button (in the center) was enabled, and the splitting procedure started again with a new direction in the anchoring position.

Data analysis

The data analysis of participants' decisions in the C-MRD consisted of three steps (for more details on the method see Lex, et al., 2012). The first step consisted of the splitting procedure to log participants' decisions. Their decisions were transformed into an Euclidian distance matrix which represents the distances between the twelve movement directions. This matrix forms the basis for the second step. The second step used the Euclidian distance matrix to perform an unweighted average-linkage cluster analysis to elicit the cognitive representation of movement directions in the form of dendrograms. In the third step, the generated representation structures have been tested for structural homogeneity by an invariance measure between groups. The statistically suggested threshold for accepting invariance is set to $\lambda_{crit} = .68$ (Lander & Huth, 1999; Schack, 2011).

Representation of movement directions by sensorimotor adaptation performance level

The last analytic step combined the results of the sensorimotor adaptation task in dependence on the representation of movement directions. Therefore, the individual adaptation performance of each participant was quantified by an adaptation index A_k (identical to Lex, et al., 2012). The adaptation index is described by the following equation,

$$A_k = \frac{AP_1 - AP_6}{AP_1 - BL_1}$$

The index k represented the participant's indicator. A_k = 100 % means a perfect adaptation back onto baseline level by the participant, whereas A_k = 0 % indicates no adaptation at all (i.e., no changes in direction of distortion compared to undistorted baseline performance). Subsequently, all participants were sorted in descending order according to their adaptation index, and separated into three groups. The first one-third represented the skilled adapters (n = 16), the second one-third the medium adapters (n =15), and the last one-third the poor adapters (n = 16). The group separation of the sensorimotor adaptation task (skilled, medium, and poor adapters) was retained for the representation of movement directions. Therefore, participants mean group dendrograms were calculated to reflect the corresponding cognitive representation of movement directions. The emerged group dendrograms were then tested for invariance.

Results

The IAE measured participant's performance in the sensorimotor adaptation task. The results of all participants showed a mean IAE for BL1 of 3.17° (SD = 1.7) and for BL2 of 3.20° (SD = 1.4). A t-test (two-tailed) revealed no differences between the baselines under different feedback conditions, t(45) = -0.143, p =.887. The mean IAE for the adaptation phases 1 to 6 have been, 33.42° (SD = 10.5), 23.14° (SD = 9.4), 17.62° (SD = 8.9), 15.01° (SD = 7.2), 14.38° (SD = 8.6), and 12.89° (SD = 7.4). An analysis of variance (ANOVA) for the adaptation phase revealed a main effect for adaptation phase, F(4.006, 172.279) = 49.249, p < .001, η2 = .534. Mauchly's Test revealed that the sphericity assumption was violated, X2(14) = 38.417, p < .001. Therefore, the degrees of freedom were corrected by estimation of sphericity according to Greenhouse-Geisser (ε = .801). Accordingly, all participants adapted to the visual disturbance over the adaptation phase. A simple contrast analysis revealed successful adaptation to all phases against the first phase (all p < .001), but adaptation gains decreased over time. The non-significant difference between the last adaptation phase (AP6) and the phase of persistence (PP), t(45) = .938, p =.353 , revealed that participants' adaptation performance persisted over time for at least five minutes.

The individual adaptation performance of the whole adaptation process was defined by an adaptation index for each participant. All participants adapted to 66.17% (SD = 26.36) towards the visual distortion. The skilled adapters (GA) showed a mean adaptation index of 89.23% (SD = 8.94), the average adapters (AA) of 71.41% (SD = 4.53), and the poor adapters (PA) of 37.51% (SD = 25.50). Figure 2.2 shows the performance curves of the skilled, the average, and the poor adapters in the sensorimotor adaptation task (a) and the mean adaptation index of all groups.

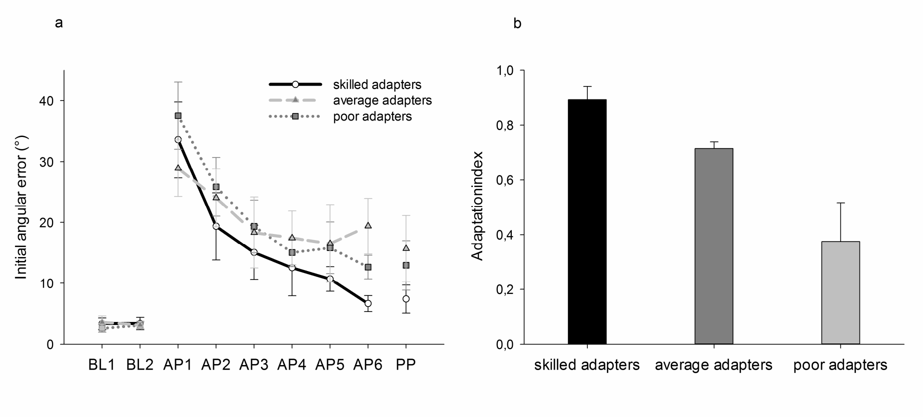

Figure 2.2 (a) Pointing performance over the phases of the skilled, average, and poor adapters in the sensorimotor adaptation task with a distortion of the visual feedback in terms of a left-right reversal.

Recorded are two different baseline phases. Baseline 1 (BL1) included visual movement feedback, and in BL2 visual movement feedback was occluded. During the adaptation phases (AP 1 to 6) and the phase of persistence (PP) visual feedback was distorted by a left-right reversal. In the PP visual feedback was occluded as in BL2. The y-axis represents the initial angular error α between the direct target direction and initial hand direction in angular degrees. The error bars indicate the 95% confidence interval. (b) The adaptation index of the sensorimotor adaptation task. The vertical bars show mean adaptation index for all three groups. The error bars represent 95% confidence interval.

In a last step, the results of the sensorimotor adaptation task have been applied onto the results of the representation of movement directions. Therefore, the group separation generated from the adaptation index was used to define the groups of skilled, average, and poor adapters and their corresponding cognitive representation of movement directions. Figure 2.3 shows the evolved cluster structures from the C-MRD of all groups. Skilled adapters' cognitive representation of movement directions included between two and three neighboring movement directions in each cluster. The evolved clusters integrated the cardinal axes in the horizontal and sagittal plane (i.e., the movement directions 1, 4, 7, and 10). Average adapters cognitive representation of movement directions showed four distinct clusters, but the movement directions 1, 7, and 8 are singled out. The cognitive representation of movement directions of the poor adapters included two neighboring movement directions per cluster. Nevertheless, all cardinal movement directions representing the main axes in the horizontal and sagittal plane (i.e. 1, 4, 7, and 10) are singled out in their respective cognitive representation of movement directions.

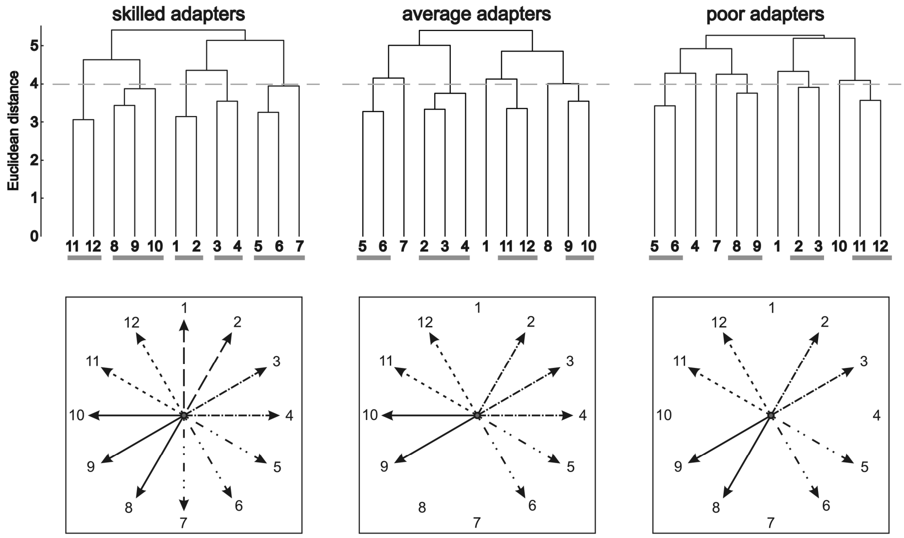

Figure 2.3 The dendrogram in the upper part show the average cluster structure of all three groups. The numbers at the bottom of each dendrogram reflect the corresponding movement direction in clockwise order starting with one in the straight upright position. The numbers at y-axis reflect the corresponding Euclidian distances for the conjunctions in the dendrogram. The grey dashed line indicates an estimated critical Euclidian distance (d_{crit} = 3.987) at which all branches of the dendrogram were cut off. The critical Euclidian distance is estimated by the application of an error probability of p = .025. All movement directions connected below that critical distance can be considered as integrated in one cluster. On the contrary, the movement directions connected above the critical distance are not integrated into a distinct cluster. Solid grey bars at the bottom indicate the evolved clusters. The bottom of Figure 2.3 displays the resulting cluster structures depicted as directional arrows. Arrows depicted in the identical manner (i.e. solid, dotted or dashed) represent a corresponding cluster in the dendrograms.

The evolved mean cluster structures of all three groups have been further analyzed to compare the resultant cognitive representation of movement directions of both groups for structural homogeneity with each other. The results of the invariance measure for the cognitive representations of movement directions showed no invariance between the groups (i.e. skilled to average adapters $\lambda = .40$, average to poor adapters $\lambda = .53$, and skilled to poor adapters $\lambda = .38$). Therefore, all groups exhibited a completely distinct cognitive representation of movement directions measured under visual stimulus presentation with regard to the sensorimotor adaptation performance. Skilled adapters possessed a global representation of movement directions (integrating the movement directions of the cardinal axes), whereas poor adapters possessed a local representation of movement directions (separating the movement directions of the cardinal axes).

An interesting side effect is observable in the cognitive representation of movement directions in skilled and poor adapters. Without regard to the statistical suggested threshold (d_{crit}), the cluster analysis connects all movement directions with each other. Two major direction-sensitive blocks were identified for all groups. Hence, the skilled adapters differentiated between movement directions on the left (8 to 10) and the right hand side (1 to 7). The average adapters' possessed a comparable representation structure (2 to 7, and 8 to 1) separating left and right. However, the poor adapters' representation indicated two direction-sensitive blocks connecting up- (10 to 3) and downward (4 to 9) directions.

Discussion

The results of the experiments provided further evidence for the impact of cognitive representations of movement directions on sensorimotor adaptation performance. Our results suggested that a global cognitive representation of movement directions is advantageous in adaptation tasks with a distortion of the visual feedback in terms of a left-right reversal. Thus, it is disadvantageous in such an adaptation task when humans possess a local representation of movement directions. Identically to a previous study conducted by Lex and colleagues (2012), the local representation of movement directions of poor adapters assembled neighboring movement directions. The peculiarity in the representation of movement directions of poor adapters was the extinction of the cardinal axes. This extinction led to a performance decrease in the sensorimotor adaptation with a distortion of the visual feedback. In contrast, the global representation of movement directions within skilled adapters led to a better performance in an adaptation task with a distortion of the visual feedback along the sagittal axis. It seems that comparable mechanisms are triggered in the activation of responsible cognitive representations of movement directions and in sensorimotor adaptation tasks. For example, the proportion of the impact of representations of movement directions on sensorimotor adaptation performance relies on the specificities of the distortion in the adaptation task. Van Beers and colleagues (2002) found evidence that the adaptation performance is dominated by proprioceptive movement feedback for azimuthally distortion (leftward), and dominated by visual movement feedback for distortions in depth (forward). Subsidiary to previous experiments conducted by Lex and colleagues (2012) it was found that adaptation performance depends on whether cognitive representations are triggered by visual or visual-proprioceptive presented movement directions. The sensory input modalities (i.e. proprioceptive-visual or visual only) of presented movement directions influenced the cognitive representation, and a main tendency was revealed. This suggests that humans possess a general cognitive representation of movement directions aligned to global (i.e. cardinal directions) or local (i.e. neighboring directions) representations of movement directions.

The adaptation towards rotated visual movement feedback can be described as direction sensitive. The direction sensitivity towards different target position has been explained by different functional modules, each pertinent to a narrow range of the response direction (Werner & Bock, 2010). In addition, a separate processing of extent and directional errors in reaching movements has been suggested, which might be planned as hand-centered vectors, whose extent and direction are established via learning a scaling factor and a reference axes (Krakauer, Pine, Ghilardi, & Ghez, 2000). Furthermore, Werner and Bock (2010) indicated that cognitive processes allowing adaptation towards reversed feedback are similar to rotated visual feedback. It has been predicted that these processes are able to change a global internal representation of space or rather multiple directions-specific modules. Based on the results of the present study, however, we provide a different argument. Our data suggests that the cognitive representation of movement directions (measured before the sensorimotor adaptation) can be interpreted as a reference frame within human motor memory. Such a cognitive reference frame influences the whole adaptation performance towards reversed visual feedback. Hence, it can be interpreted as a direction-specific and overarching module in human motor memory (comparable to Tanaka, Worringham, & Kerr, 2009). However, further research is needed to investigate the influence of the cognitive representation of movement directions on adaptation towards rotated visual feedback to strengthen such an argument.

Further evidence is provided by experiments where the participants adapted towards different distortions (i.e. visual and mechanical) with normal or impaired proprioceptive feedback. The results showed that intact proprioception is needed for adaptation towards a mechanical distortion, but not towards a visual distortion. Both sensory modalities seemed to be independent from each other (Pipereit, Bock, & Vercher, 2006). In accordance to the present study, it can be assumed that cognitive structures, like representations of movement directions, are involved in adaptation tasks. Moreover, there is additional neurophysiologic evidence for the existence of a movement related system, which encodes movement directions in the motor cortex. Comparable neuronal activity was measured in the motor cortex, when reaching movements were executed in specific movement directions (Georgopoulos, 2000; Georgopoulos, Caminiti, Kalaska & Massey, 1983; Georgopoulos, Kalaska, Caminiti & Massey, 1982; Georgopoulos, Schwartz & Kettner, 1986). Thus, the cognitive representation of movement directions can be considered as a cognitive structure, which is relevant in direction sensitive sensorimotor adaptation tasks. It remains speculative that cognitive representations of movement directions will be activated during other direction sensitive complex motor actions. More research needs to be conducted to verify such a bold idea.

Altogether, it can be proposed that the cognitive representation of movement directions may be considered as an indicator for measuring adaptation performance in pointing tasks with a visual disturbance in terms of a left-right reversal. Moreover, it can be concluded that the representation structure seems to be a valid predictor for sensorimotor adaptation performance.

References

Abeele, S., & Bock, O. (2001). Mechanisms for sensorimotor adaptation to rotated visual input. Experimental Brain Research, 139(2), 248-253. doi:10.1007/s002210100768

Bock, O. (2005). Components of sensorimotor adaptation in young and elderly subjects. Experimental Brain Research, 160(2), 259-263. doi:10.1007/s00221-004-2133-5

Bock, O., & Girgenrath, M. (2006). Relationship between sensorimotor adaptation and cognitive functions in younger and older subjects. Experimental Brain Research, 169(3), 400-406. doi:10.1007/s00221-005-0153-4

Bock, O., Schneider, S., & Bloomberg, J. (2001). Conditions for interference versus facilitation during sequential sensorimotor adaptation. Experimental Brain Research, 138(3), 359-365. doi:10.1007/s002210100704

Ferrel, C., Bard, C., & Fleury, M. (2001). Coordination in childhood: modifications of visuomotor representations in 6-to 11-year-old children. Experimental Brain Research, 138(3), 313-321. doi:10.1007/s002210100697

Georgopoulos, A. P. (2000). Neural aspects of cognitive motor control. Current Opinion in Neurobiology, 10(2), 238-241. doi:10.1016/S0959-4388(00)00072-6

Georgopoulos, A. P., Caminiti, R., Kalaska, J. F., & Massey, J. T. (1983). Spatial coding of movement: A hypothesis concerning the coding of movement direction by motor cortical populations. Experimental Brain Research, Supplement 7, 327-336

Georgopoulos, A. P., Kalaska, J. F., Caminiti, R., & Massey, J. T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. The Journal of Neuroscience, 2(11), 1527-1537

Georgopoulos, A. P., Schwartz, A. B., & Kettner, R. E. (1986). Neuronal population coding of movement direction. Science, 233(4771), 1416-1419

Ingram, H. A., van Donkelaar, P., Cole, J., Vercher, J. L., Gauthier, G. M., & Miall, R. C. (2000). The role of proprioception and attention in a visuomotor adaptation task. Experimental Brain Research, 132(1), 114-126. doi:10.1007/s002219900322

Krakauer, J. W., Pine, Z. M., Ghilardi, M. F., & Ghez, C. (2000). Learning of visuomotor transformations for vectorial planning of reaching trajectories. Journal of Neuroscience, 20(23), 8916-8924.

Lander, H. J., & Huth, M. (Eds.). (1999). Ein Verfahren zur Ermittlung der Strukturierung und Dimensionierung begrifflich repräsentierten Wissens im Langzeitgedächtnis [transl. A method to ascertain the structure and the dimensioning of conceptually represented knowledge in long-term memory). Leipzig: Universitätsverlag.

Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2012). Functional relationship between cognitive representations of movement directions and visuomotor adaptation performance. Experimental Brain Research, 223(4), 457-467. doi:10.1007/s00221-012-3273-7

Mazzoni, P., & Krakauer, J. W. (2006). An implicit plan overrides an explicit strategy during visuomotor adaptation. The Journal of Neuroscience, 26(14), 3642-3645. doi:10.1523/JNEUROSCI.5317-05.2006

Miall, R. C., Jenkinson, N., & Kulkarni, K. (2004). Adaptation to rotated visual feedback: a re-examination of motor interference. Experimental Brain Research, 154(2), 201-210. doi:10.1007/s00221-003-1630-2

Pipereit, K., Bock, O., & Vercher, J. L. (2006). The contribution of proprioceptive feedback to sensorimotor adaptation. Experimental Brain Research, 174(1), 45-52. doi:10.1007/s00221-006-0417-7

Redding, G. M., & Wallace, B. (1996). Adaptive spatial alignment and strategic perceptual-motor control. Journal of Experimental Psychology: Human Perception and Performance, 22(2), 379-394. doi:10.1037/0096-1523.22.2.379

Schack, T. (2011). Measuring Mental Representations. In G. Tenenbaum, et al. (Eds.), Handbook of Measurement in Sport and Exercise Psychology (Vol. 1). Champaign, Illinois: Human Kinetics.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. Neuroscience Letters, 391(3), 77-81. doi:10.1016/j.neulet.2005.10.009

Tanaka, H., Worringham, C., & Kerr, G. (2009). Contributions of vision–proprioception interactions to the estimation of time-varying hand and target locations. Experimental Brain Research, 195(3), 371-382. doi:10.1007/s00221-009-1798-1 van Beers, R. J., Wolpert, D. M., & Haggard, P. (2002). When feeling is more important than seeing in sensorimotor adaptation. Current Biology, 12(10), 834-837. doi:10.1016/S0960-9822(02)00836-9

Werner, S., & Bock, O. (2010). Mechanisms for visuomotor adaptation to left-right reversed vision. Human Movement Science, 29(2), 172-178. doi:10.1016/j.humov.2010.02.004

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. Science, 269(5232), 1880-1882. doi:10.1126/science.756993

Representation in Manual Actions – II

CHAPTER 3

Abstract The aim of our study was to explore whether or not different types of learners in a sensorimotor task possess characteristically different cognitive representations. Participants' sensorimotor adaptation performance was measured with a pointing paradigm, which used a distortion of the visual feedback in terms of a left–right reversal. The structure of cognitive representations was assessed using a newly established experimental method, the Cognitive Measurement of Represented Directions. A post hoc analysis revealed inter-individual differences in participants' adaptation performance, and three different skill levels (skilled, average, and poor adapters) have been defined. These differences in performance were correlated with the structure of participants' cognitive representations of movement directions. Analysis of these cognitive representations revealed performance advantages for participants possessing a global cognitive representation of movement directions (aligned to cardinal movement axes), rather than a local representation (aligned to each neighboring direction). Our findings are evidence that cognitive representation structures play a functional role in adaptation performance.

This chapter is a revised version of Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2012). Functional relationship between cognitive representations of movement directions and visuomotor adaptation performance. Experimental Brain Research, *223*(4), 457-467.

Introduction

In daily life, humans must constantly adapt to the incongruencies between the expected and perceived effects of our goal-directed or automated actions on the environment. Such surprising incongruencies drive the establishment of new links between sensory input and motor output and allow humans to adapt to changes in environmental conditions. Many laboratory studies have investigated adaptation processes by conducting experiments in which participants execute straight ballistic pointing movements toward targets (e.g., Georgopoulos, Caminiti, Kalaska, & Massey, 1983; Georgopoulos, Kalaska, & Massey, 1981), or track a moving target on a screen (e.g., Abeele & Bock, 2003). The adaptation paradigm can be described as follows: After participants are familiarized with the setup, they are introduced to a distortion and their task performance is measured over a number of trials. Usually, performance errors peak immediately after distortion onset and normalize again with extended practice. This sensorimotor adaptation phenomenon has been studied in the context of different distortions, such as visual (Bock & Girgenrath, 2006) and mechanical (Pipereit, Bock, & Vercher, 2006) distortions. It is well accepted that sensorimotor adaptation, as signified by specific performance improvements, is initiated by two different types of processes: The first process involves the gradual recalibration of the sensorimotor system, while the second process involves strategic control (Bock, 2005). Essentially, this recalibration process brings sensory input and motor output in accordance with each other to control for the distortion. This adaptive behavior is initiated by the transformation of an internal model (Wolpert, Ghahramani, & Jordan, 1995) or a ‘spatial realignment’ (Redding & Wallace, 1996) and can be described as a stepwise approximation to new environmental conditions. The strategic control process is grounded in cognitive schemes and representations, which are activated to overcome, for example, the performance disruption at the beginning of trials (Redding & Wallace, 1996). Therefore, visual feedback-based movement adjustments and anticipatory mechanisms control the movement's execution. These processes are active when, for instance, closed boxes are lifted without any knowledge about their weight. After the first box was carried, it is possible to anticipate the weight of the second box in a better way, and the grip force will be immediately adjusted in advance.

Functional links between sensorimotor adaptation and cognitive functions, which are potentially the basis of this link, are often discussed. For example, when performing a sensorimotor task requiring some sort of adaption, participants' adaptive performance is better when attention is distributed between the target and cursor, rather than focusing mainly on the target or spreading attention across the whole scenario (Grigorova, Petkova, & Bock, 2006). Decreased adaptive performance in sensorimotor adaptation tasks is found among the elderly and might be caused by changes to the cognitive structures involved in decision-making and basic response speed (Bock & Girgenrath, 2006).

A study highlighting not only the role of cognition in sensorimotor performance but also the necessity of possessing stored mental representations comes from Ingram, van Donkelaar, Cole, Vercher, Gauthier, and Miall (2000). These authors showed that a deafferent patient (i.e. a neurological disorder, where the patient has no sensory input from his neck downwards) is able to adapt toward visual distortions (e.g. immediate and gradual gain change) in a goal-directed arm movement task when a distortion (e.g. 1.5 times gain change) was applied. However, an additional cognitive task (e.g. counting task) impaired his adaptation performance severely for more than a 60 % change. In comparison, the adaptation performance gain of the control group was also impaired, but only less than 10 %. It is important to note that in order to adapt in this task, the deafferent patient had to rely predominantly on his cognitive structures, without receiving any proprioceptive feedback from his arm movements. Ingram and colleagues (2000) concluded that proprioception is not an absolute requirement for adaptation. Rather proprioception is only one relevant part in the ability to adapt for visuomotor distortions.

Each of these studies mentioned so far (Bock & Girgenrath 2006; Grigorova, Petkova, & Bock, 2006; Ingram et al., 2000) underlines the important role of cognition in sensorimotor adaptation. Their results support the viewpoint that the storage of information about movements and their interaction with the environment form the basis of learning processes. Still, these studies have merely speculated about the structure of cognitive representations. The present study takes a more direct attempt to measure the link between sensorimotor adaptation performance and cognitive representations.

Researchers from fields such as cognitive psychology and cognitive robotics (Maycock, Dornbusch, Elbrechter, Haschke, Schack, & Ritter, 2010; Schack, 2004; Schack & Mechsner, 2006; Schack & Ritter, 2009; Stöckel, Hughes, & Schack, 2011) have provided evidence for the functional role of cognitive representations in the control of human movements. According to these studies, structured cognitive representations of motor actions base on so-called basic action concepts (BACs). Analogous to the well-established notion of basic concepts in the world of objects (Mervis & Rosch, 1981), BACs can be viewed as the mental counterparts of functionally relevant elementary components or transitional states (body postures) of complex movements (Bläsing, Tenenbaum, & Schack, 2009; Schack & Ritter, 2009; Weigelt, Ahlmeyer, Lex, & Schack, 2011). They base on the cognitive 'chunking' of body postures and movement events, which possess common functions involved in the realization of action goals. Unlike object concepts, BACs do not refer to behavior-related invariance properties of objects, but rather to perception-linked invariance properties of movements.

For example, Schack and Mechsner (2006) studied the tennis serve to investigate the nature and role of long-term memory in skilled athletic performance. Using the Structural Dimensional Analysis of Mental Representations (Schack, 2004; 2011), the authors analyzed high-level experts and found that the structures of their representations were organized in a distinctive tree-like hierarchy, were remarkably similar between individuals, and were well-matched with the functional and biomechanical demands of the task. In comparison, the structures of action representations in low-level players and non-players were organized less hierarchically, were more variable between persons, and were not as well matched with the functional and biomechanical demands of the task. The results of related studies from a variety of disciplines (e.g. manual action, judo, wind surfing, dancing) have further demonstrated that cognitive representation structures in long-term memory are functionally related to performance (Bläsing, 2010; Bläsing, Tenenbaum, & Schack, 2009; Schack & Hackfort, 2007; Stöckel, Hughes, & Schack, 2011; Weigelt, Ahlmeyer, Lex, & Schack, 2011).

It can be inferred from these studies that these cognitive representation structures consisting of cognitive units (such as basic action concepts in complex motor actions) are also involved in smaller motor actions (such as pointing movements in a sensorimotor task). One functionally relevant basic cognitive unit in goal-directed pointing movements might be a representation of a movement direction.

Research in neurophysiology has provided convincing evidence for the existence of such cognitive representations of movement directions (Georgopoulos, Schwartz, & Kettner, 1986). Cognitive spatial-motor processes were investigated by the application of setups indicating movement directions by center-out movements toward flashed up lights. One of the earliest studies measured a significant linear increase in reaction time, when the rotation angle between a defined stimulus direction and the required movement direction increased (Georgopoulos & Massey, 1987). From this finding, it was derived that performing such tasks involves a mental rotation of an imagined movement vector about its origin. Additionally, neurophysiological correlates sensitive to movement directions were found in the brains of monkeys (Georgopoulos, Caminiti, Kalaska, & Massey, 1983). A first process in the brain indicates that directional information about visually cued arm movements (i.e. indicated by turned on peripheral lights) is encoded and can be visualized by the analysis of the neuronal population vector. A second process indicates that representations of movement directions are related to retention mechanisms in long-term memory. This is because in the absence, rather than in the presence, of a visual target, the neurophysiological signals become significantly stronger (Smyrnis, Taira, Ashe, & Georgopoulos, 1992). Caminiti, Johnson, and Urbano (1990) found that neuronal population responses are more related to movement trajectories than to end-points of movements, which highlights the relevance of directions in goal-oriented pointing movements. Thus, a direction sensitive neuronal population vector can serve as a predictor for the directions in which goal-oriented pointing movements are executed (Caminiti et al., 1991). In contrast, to findings of directional sensitive neurons in frontal areas, there is evidence that neurons in parietal lobe Brodmann area 5 are tuned positionally during movement and stationary posture. Spatial coordinates defining the azimuth, elevation, and distance during reaching movements characterize this positional tuning. Each of the spatial coordinates might be encoded discretely in distinct subpopulations of neurons. These neurons form classes described by a fixed tuning function. ‘Initial position’ neurons movement activity does not change in relation to the starting point of the movement. ‘Variational’ neurons are related to the difference vector between final and initial position, which is responsible for the encoding of movement direction (Lacquaniti, Guigon, Bianchi, Ferraina, & Caminiti, 1995). Thus, in parietal lobe area 5, movement directions are encoded in populations of neurons. Additionally, a subset of neurons found to be sensitive to preset distortion change their activity during sensorimotor adaptation. These neurons acquire directional sensitivity to the adapted direction, but this sensitivity has a limited generalization ability for all other directions (Paz & Vaadia, 2009). This experimental evidence highlights the functional relevance of movement direction in goal-directed movements on a neurophysiological level.

From our point of view, sensorimotor adaptation of manual actions has to be planned and represented in terms of intended perceptual effects and future task demands. Therefore, individuals are developing structured cognitive representation of movement directions in order for the movement to be carried out and adapted successfully.

Neurophysiologic evidence supports the notion that movement directions are represented in long-term memory. Therefore, it can be assumed that the sensorimotor adaptation performance in goal-directed pointing movements is fundamentally influenced by the structure of cognitive representations of movement directions.

The present study investigates individuals' cognitive representations of movement directions from long-term memory and evaluates their influence on sensorimotor adaptation performance. With this study, we attempt to examine the functional relationship between cognitive representations and sensorimotor adaptation, and the extent to which the variation in individual adaptive ability correlates with the variation in representation structures in long-term memory. From that point of view, this will be the first study to examine individual differences in adaptive ability and its underlying cognitive sources.

Methods

Data were collected from students at Bielefeld University (26 women and 19 men; mean age 23.7 years, standard deviation 4.7 years). The participants provided written consent prior to the experiments and did not receive any financial compensation. The research study was approved by the local ethics committee and conducted in accordance with the 1964 Declaration of Helsinki. All participants completed two experiments. First, they performed a standard sensorimotor adaptation task, which required center-out pointing movements to different target locations regularly distributed on a circle. Second, they judged visual and proprioceptive movement directions using the Cognitive Measurement of Represented Directions (C-MRD).

Sensorimotor adaptation task

The sensorimotor adaptation task was executed by all participants to measure their adaptive performance before and after the left–right reversal distortion of visual feedback.

Apparatus and task

Adaptive performance was assessed using a standard pointing experiment, in which pointing movements are executed on a digitizer tablet (Genius NewSketch 1812HR). Participants sat in front of a 15-inch standard monitor facing downwards (see Figure 3.1). To ensure a stable and constant position throughout the whole experiment, participants leaned their head against a foam cushion fixed to the monitor at a height of 130 cm. Visual real-time feedback of hand movements was provided by a red cursor cross (8 mm in length and width) displayed on the screen. Vision of the screen was available indirectly, through a tilted mirror. The mirror occluded vision of the individual's own hand in order to prevent the use of visual control strategies on the hand movements. Screen-to-mirror and mirror-to-digitizer tablet distance was adjusted to 21.5 cm each. Hence, all projected images of target dots, center location, and the red cursor-cross appeared in the same plane of working space. A height-adjustable chair assured a comfortable position and permanent visibility of the complete screen.

The participants' task was to execute straight and ballistic (i.e. open loop) center-out movements toward one of eight randomly appearing, equidistant, peripheral target locations as accurately as possible. Similar to previous studies that used this standard sensorimotor adaptation task (cf. Bock, 2005; Bock & Girgenrath, 2006; Miall, Jenkinson, & Kulkarni, 2004), the center location always served as the start position for the next movement. The target locations were yellow dots sized 8 mm in diameter, displayed on a black background in an arc radius of 10 cm. The target dots stayed on the screen until they were reached by the cursor cross or for a maximum of 700 ms. If participants failed to reach the target location, a new target automatically appeared on the screen after five seconds. Within each 30 s trial, as many pointing movements as possible were executed. The intertrial interval was set to five seconds.

The experiment started with three practice trials, to familiarize participants with the setup. Afterward, baseline data were collected for five undistorted trials with normal vision in Baseline 1 (BL1), followed by five undistorted trials without vision of the red cursor cross in Baseline 2 (BL2).

During BL2 trials, participants were forced to execute the pointing movements more intuitively, because the red cursor cross disappeared when participants moved more than 10 mm away from the center position, and appeared again when they re-entered this area. Participants still needed the cursor cross to find their way back to the center position and move on to the next movement target. During the adaptation phase (AP), the (normal) visual feedback relationship between sensory input and motor output was distorted by a left–right reversal mirrored along the sagittal axis (i.e. 180_ rotation). For example, in this condition, participants would need to execute a pointing movement toward the upper right corner if they wanted to reach the upper left corner. Full visual feedback of the cursor cross was provided in the adaptation phase, which consisted of 30 trials. After a five minutes break, five distorted trials without full visual feedback were performed in the phase of persistence (PP) to test for the persistence of adaptive behavior over time.

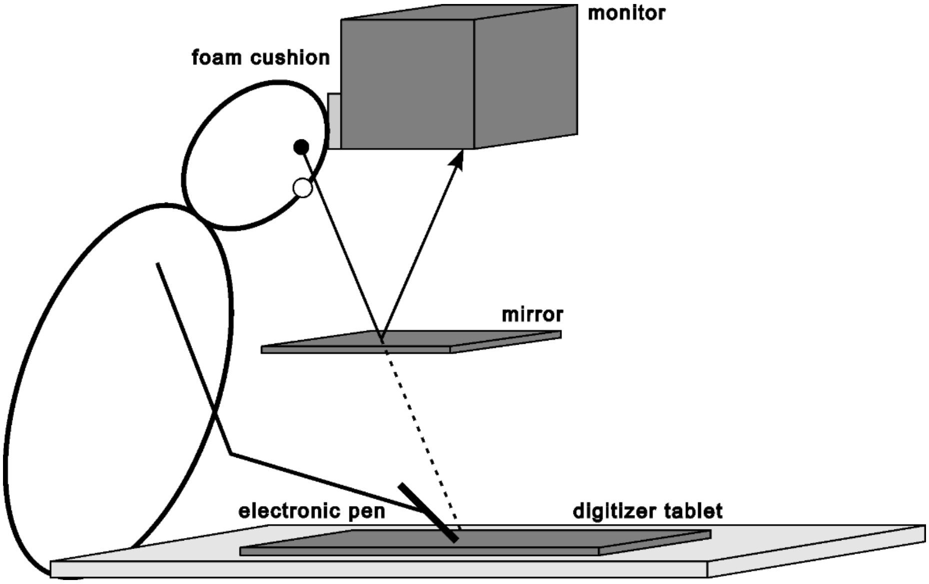

Figure 3.1 Experimental setup of sensorimotor adaptation task. Participants moved an electronic pen in one of eight movement directions indicated by yellow dots on a black background. The projection of the screen was provided by a tilted mirror, which occluded vision of the participant's own hand as they executed the task. Target dots appeared in the working plane. Participants leaned their head against a foam cushion to ensure a stable, constant position

Data analysis

To quantify participants' pointing performance, the initial angular error (IAE) was measured for each pointing movement. The IAE was defined as the difference between the straight target direction and the initial hand movement direction. Thereby, the straight target direction was defined as the direct line between the hand position at movement onset (the start position) and the target location. The initial hand movement direction was defined as the line between the hand position at movement onset and the location of the hand when the first peak velocity was reached. To exclude small corrective adjustments, the critical minimal cursor velocity was set to 30 mm/s. This error detection mechanism was used because it is largely unaffected by the visual feedback-based corrective modifications which occur during the later phases of a single pointing movement. The IAE was averaged over all executed pointing movements and then aggregated into phases. To compare phases of identical length, each phase consisted of the average IAE of five consecutive trials. An analysis of variance (ANOVA) with repeated measures was conducted to verify differences between the adaptation phases.

Cognitive representation of movement directions

For use in this study, the C-MRD was developed to be specifically applicable to the assessment of the cognitive representations of movement directions. The applied sensorimotor task consisted of pointing movements in distinct directions. Thus, movement directions are the physically relevant features for the sensorimotor adaptation task. The C-MRD method investigates the cognitive representations of movement directions as relevant features. Participants experienced all movement directions (i.e. cognitive units) used in this method both visually and proprioceptively. Van Beers, Wolpert, and Haggard (2002) gave the reason that the movement directions have to be experienced by the described input modalities. They showed evidence that sensorimotor adaptation performance relies on the contribution of proprioceptive feedback as well as on the contribution of visual feedback when adapting toward a visual distortion in terms of sagittal displacement (van Beers et al., 2002). The present study is planned to learn about the relationship between adaptation behavior and cognitive representations. Thus, the measurement of cognitive representations of movement directions must integrate proprioceptive features as well as the visual feedback of executed movement directions as two integral components of the cognitive representations. For this reason, both input modalities were integrated in the measurement of the cognitive representations of movement directions. Consequently, the conditions of the sensorimotor adaptation task and the C-MRD task were matched as much as possible.

Apparatus and task

Participants sat in front of an apparatus, which was on a table (see Figure 3.2). Participants' cognitive representation of movement directions was assessed using a splitting procedure, that is, a comparison of each movement direction with every other direction, but not with itself. In this splitting procedure, participants were asked to grasp a wooden stick in the center position of the apparatus and move it once to the lit up target direction. The twelve target directions were distributed at equidistant intervals around a circle. For each direction, there was a slot in the wooden platform to guide the wooden stick outward from the center. As soon as stick reached the end of the slot, the movement was redirected to the center position. There was a brief rest break before the experimenter lighted up the next target direction. After two consecutively executed movements into different slots, participants were asked to judge based on their own subjective criterion whether the two executed movement directions appeared similar to them, or different. They did not state verbally whether the two executed movement directions are the same, or different. Furthermore, decisions were allocated to a positive (i.e. if movement directions were judged as similar) or a negative (i.e. if movement directions were judged as dissimilar) subset and logged on a standard personal computer by the experimenter immediately after participants’ answered verbally. Decisions were made without any time limits. One randomly chosen movement direction remained in the reference position (first of the two movements performed) until it was compared with every other movement direction (second movement performed). Once all decisions for the reference direction were completed, another movement direction became the reference position. This process lasted until all possible combinations of movement directions had been compared. The splitting procedure revealed insight into the general formation of cognitive units (i.e. movement directions).

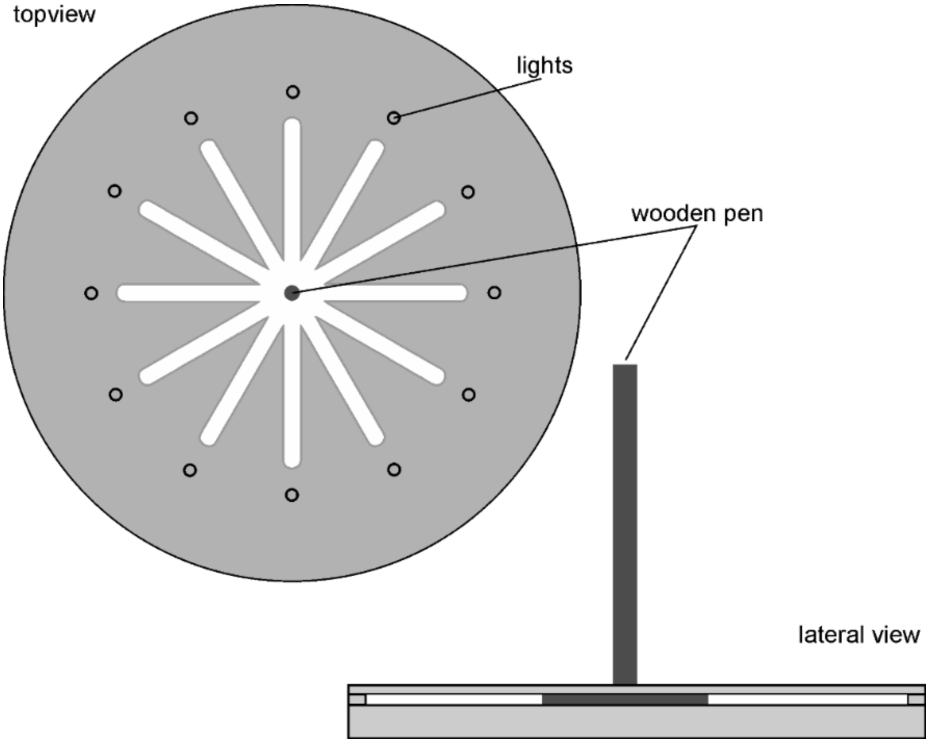

Figure 3.2 Experimental setup to measure the cognitive representation of movement directions. The apparatus consisted of twelve movement directions indicated by 12 slots in a wooden plate. All movement directions were spread equally around a circle, starting with the first slot in the straight upward position and another slot at each 30° rotation. Participants received visual and proprioceptive feedback from their movements as they moved a wooden pen in the direction of a lit up target. After two executed movements, participants made subjective judgments about similarity

Data analysis

The data analysis of participants' decisions consisted of three steps. First, for each reference direction, the described splitting procedure created a positive and a negative subset of movement directions. Movement directions in each subset were assigned a score reflecting their similarity to the reference direction. The score was based on the number of elements in the subset and the sign of the subset (positive/ negative). This procedure resulted in a score vector for each reference direction. The score vectors of all reference directions were concatenated into a score matrix. Each row of the score matrix corresponded to one reference direction. Rows were transformed by a z-normalization, and converted to a relative position of each reference direction in a multidimensional direction space. This normalized position matrix was then used to calculate the Euclidian distances between all reference directions, resulting in a distance matrix. Second, the representations of movement directions were calculated using an unweighted average-linkage hierarchical cluster analysis applied to the Euclidian distances matrix. The numbers at the conjunctions within each dendrogram (i.e. cluster structure) reflect the distance between a given pair of directions. The smaller the Euclidian distance between two directions, the more similarly the two directions were subjectively perceived, and the closer they are represented together in human long-term memory. The critical Euclidian distance is statistically estimated as the value $d_{crit} = 4.552$ for a significant alpha-level of $p = .01$. All connected structures below the critical value form distinct clusters. Conversely, all movement directions with a Euclidian distance above the critical value are not integrated into distinct clusters. Third, the generated representations of movement directions were tested for structural homogeneity using a within- and between-groups invariance measure. In the present analysis, the statistical threshold for accepting invariance between two structures is set to $k = .68$ (Schack, 2004).

Representation of movement directions by adaptive performance level

Finally, participants' cognitive representations of movement directions were assessed with regard to their sensorimotor adaptation performance. This analysis connected the results of the sensorimotor adaptation task with participants' cognitive representation structures.

Therefore, individual sensorimotor adaptation performance was quantified by an adaptation index (A_k, Bock & Girgenrath, 2006). This index (A_k) compares the IAE at distortion onset (AP1), subtracted by the error in the last adaptation phase (AP6), in relation to the error at distortion onset (AP1), subtracted by baseline error (BL1). The adaptation index is calculated as

$$A_k = \frac{AP_1 - AP_6}{AP_1 - BL_1}$$

where k is the participant's indicator. An A_k of 1.0 indicates perfect adaptation back to the baseline performance level, whereas an A_k of zero indicates no adaptation at all, that is, no performance improvement compared with baseline level. The adaptation index is used as a criterion to quantify participant's adaptation performance by a semi-quantitative analysis (Abeele & Bock, 2003; Bock & Girgenrath, 2006). After the calculation of the adaptation index for each participant, they were sorted according to their adaptation index, and ranked in a descending order. The whole list of participants was then split into three equal thirds. The top third of participants were classified as skilled adapters, the middle-third as average adapters, and the lower third as poor adapters. Depending on the individual adaptation performance indicated by the adaptation index within each sub-group (i.e. skilled, average, and poor adapters), the cognitive representations were analyzed by calculating the mean cluster solutions for the three categories of adapters.

The resulting subgroup dendrograms were tested for structural homogeneity (i.e. invariance measure between evolved cluster solutions) to verify skill-related differences based on the cognitive representation structure.

Results

Figure 3.3a illustrates the time course of the IAE in the sensorimotor adaptation experiment for each group. For all participants, the results of the ANOVA with repeated measures showed a main effect for the factor phase, $F(3.4, 147.6) = 30.358$, $p < .001$. Mauchly's test revealed that the sphericity assumption was violated, $X^2(14) = 53.379$, $p < .01$. Therefore, the degrees of freedom were corrected by estimation of sphericity according to Greenhouse–Geisser ($\varepsilon = .671$). A simple contrast analysis of all adaptation phases revealed successful adaptation during all phases in contrast to the first phase ($p < .001$). A non-significant difference between adaptation phase six and the phase of persistence, $t(44) = .850$, $p = .40$ (2-tailed), indicated that participants' adaptation behavior persisted over time.

The adaptation index quantified participants' adaptation performance in comparison with the undistorted baseline condition. Participants adapted to 61 % toward the distortion of the visual feedback in terms of a left–right reversal, indicated by $A_k = 0.61$ ($SD = 0.28$). Figure 3.3b shows the results of the third split, after sorting participants in a descending order according to their adaptation index, starting with the best adapters. In contrast to average (A_k = 0.66; SD = 0.08) and poor adapters (A_k = 0.28; SD = 0.14), skilled adapters (A_k = 0.90; SD = 0.06) nearly reached their baseline performance again.

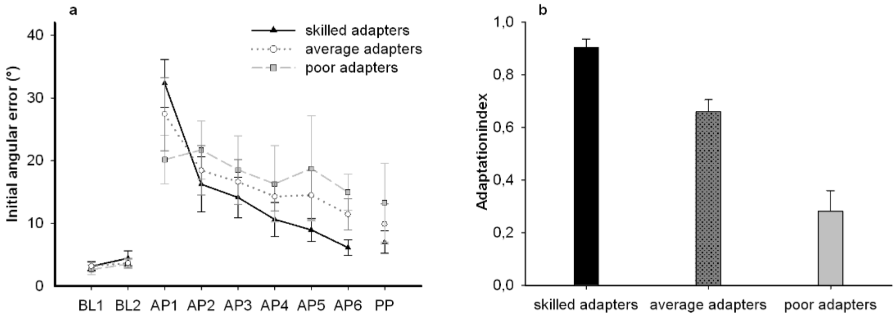

Figure 3.3 (a) Adaptive behavior toward a distortion of visual feedback, including undistorted baseline conditions. The data points show the mean IAE (the difference between initial hand direction and target direction) as a function of trials in the study for each group. Five consecutive trials are aggregated into each phase. The phases represent the baseline (BL) phases one and two, the adaptation phases (AP) one to six, and the phase of persistence (PP). The error bars represent a 95 % confidence interval. (b) Adaptation index of visuomotor adaptation task. Vertical bars show mean adaptation index of the skilled (SA), average (AA), and poor adapters (PA). Error bars represent a 95 % confidence interval. Adaptation index of Ak = 1.0 represents adaptation performance back on baseline level. Adaptation index of Ak = 0.0 represents no adaptation toward the visual distortion

To link the groups formed by the adaptation index to the cognitive representation structures, the mean cluster solutions of the cognitive representations were calculated in the last analytic step. Figure 3.4

illustrates the dendrograms (i.e., cluster structures) which resulted from the cluster analysis, including an illustration of the cluster structures depicted as directional arrows. The cluster structures display the mean cognitive representation structure of movement directions for each adaptation group. The dashed gray horizontal line indicates the critical value $d_{crit} = 4.552$ for a significant alpha-level of $p = .01$. The numbers at the bottom indicate the movement directions, starting with one in the straight upward position and continuing at each 30° interval.

The mean representation structure of the skilled adapters group consists of three clusters. Not all movement directions are integrated in the evolved cluster structures. It is also interesting that one cluster consists exclusively of two cardinal movement directions (10 and 4), indicating the importance of these directions in the cognitive representation structure. The representation of movement directions for this group is strongly aligned to the cardinal axes (i.e. the sagittal and horizontal axis). Average adapters' mean representation structure shows the integration of all movement directions and the formation of four cluster structures. The resulting dendrograms integrate movement directions along the cardinal axes, but not as prominently, as is seen in the skilled adapters group. The mean cognitive representation structure for poor adapters forms six clusters integrating two movement directions each. Thereby, every two neighboring movement directions form a coherent cluster structure. The movement directions in the cardinal axes did not show a greater prominence than other movement directions for this group, in contrast to the other two groups.

The evolved cluster structures were tested for structural homogeneity (i.e. invariance) between all three groups. The suggested statistical threshold for accepting invariance between different cluster solutions is defined as $\lambda = .68$. The comparison between cluster solutions of all groups with each other showed no invariance between groups: $\lambda_{SA\ to\ AA} = .41$, $\lambda_{AA\ to\ PA} = .37$, and $\lambda_{SA\ to\ PA} = .30$. Skilled adapters’ global representation of movement directions (aligned to cardinal axes) is advantageous compared with poor adapters’ local representations of movement directions (not aligned to cardinal axes, but rather aligned to neighboring directions) with regard to the sensorimotor adaptation task. Having a global representation of movement directions is advantageous in the herein applied sensorimotor adaptation task because of the functional relation to the used visual distortion.

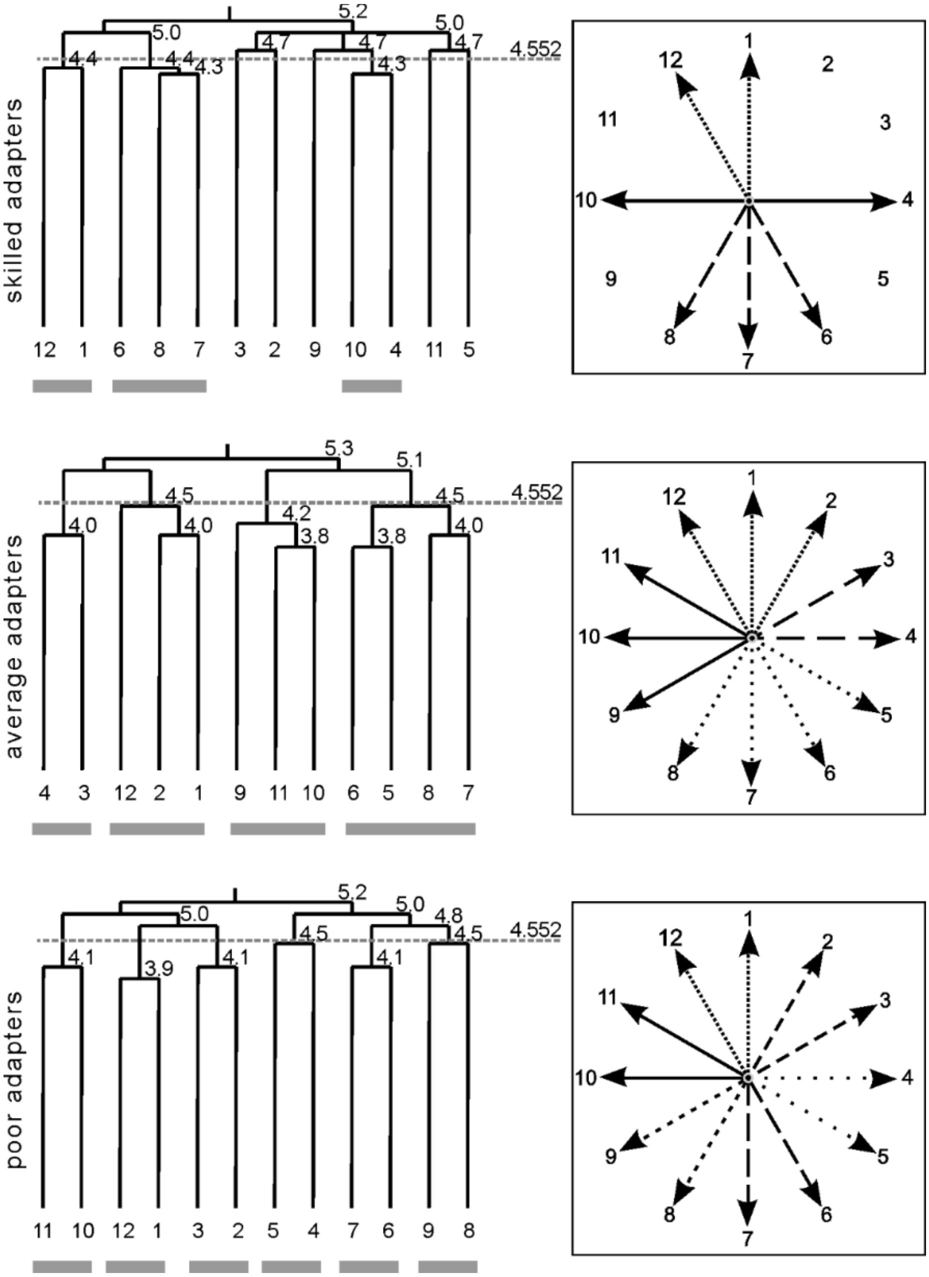

Figure 3.4 Cognitive representation of movement directions. Dendrograms (left) show the results of the three groups. The numbers at the bottom show the movement directions continuously increasing every 30° starting with 1 in the straight upward position. To reflect

remoteness between a given pair of directions, the numbers at the conjunctions indicate corresponding Euclidian distances. The resulting cluster structures (indicated by solid gray bars at the bottom) are revealed by a critical value d_{crit} = 4.552 for a significant alpha-level of p = .01 marked by the horizontal gray dashed line. On the right-hand side of each dendrogram, directional arrows pointing into the corresponding movement directions illustrate identical cluster solution. Arrows depicted in identical manner (dashed, dotted, or solid) represent the clusters in the dendrograms

Discussion

The results of these experiments present evidence for a link between cognitive representations of movement directions and sensorimotor adaptation performance. It was found that having a global cognitive representation of movement directions aligned to the cardinal movement axes in the sagittal and horizontal planes is beneficial in an adaptation task, which has a mirroring of visual feedback along the sagittal axis. On the contrary, having a local cognitive representation of movement directions diminishes adaption performance in the same sensorimotor task.

These experiments enable us to give the first insights into how movement directions are stored in human long-term memory on a cognitive level. This information allows us to expand already existing findings about the memory related neurophysiologic mechanisms, which underlie the execution of goal-directed pointing movements in distinct movement directions (cf. Georgopoulos, Schwartz, & Kettner, 1986; Wu & Hatsopoulos, 2006; 2007).

Interestingly, the present results relate well to findings from neuropsychological research on patients. In an early study, Bálint (1909) investigated a patient with a bilateral parietal lesion having difficulties in executing accurate reaching movements. Usually, parietal patients are unable to match information about target location, eye and hand position, and movement direction. Moreover, neurons in the superior parietal lobe can be regarded as directionally sensitive (Battaglia-Mayer & Caminiti, 2002). Within parietal patients, it can be distinguished, for instance, between two different cognitive-motor disorders: optic ataxia and directional hypokinesia. Optic ataxia is characterized by a disordered composition and control of directional hand movements (i.e. end-point errors of hand movements) in the absence of visual feedback (Caminiti et al. 2010). However, proprioceptive and tactile information can help to execute directional hand movements more accurately (Kolb & Whishaw, 1996). Directional hypokinesia is characterized as an impaired representation of action space. This lesion prohibits normal movement execution toward targets in the contralesional part of egocentric space. This is preferentially described by a prolonged reaction and movement time (Caminiti, Chafee, Battaglia-Meyer, Averbeck, Crowe, & Georgopoulos, 2010). This means that patients with optic ataxia performing with impaired components (e.g. general motor programs) are responsible for motor execution. The representation of space is not impaired, because other movement feature dimensions (i.e. proprioceptive or tactile movement feedback) can help to reach the target appropriately (Kolb & Whishaw, 1996). People with directional hypokinesia possess an exact movement execution, but they refer to impaired, respectively, wrong space representations. Finally, the reaching disorder in optic ataxia does not show the strict directional polarity (i.e. or hemispherical effects), as has been described for directional hypokinesia (Battaglia-Mayer, Mascaro, Brunamonti, & Caminiti, 2005). The experiment found advanced adaptation behavior for participants who possess a cognitive representation of movement directions functionally related to the visual distortion in the adaptation task. Thus, it could be speculated that people with optic ataxia possess functionally organized representations of movement directions, whereas people with directional hypokinesia do not possess such representation structures. Although, now, this is mere speculation about the cognitive representation of movement directions in these patients and more research on this topic is necessary. In the future, it therefore seems interesting to investigate patients with these disorders in order to learn more about their representations of movement directions. Another interpretation could lead to a speculation about the application of functional reference axes. It is possible that patients with such disorders (i.e. directional hypokinesia or optic ataxia) possess different abilities in the recognition of inconsistencies between a reference axis and afforded movement directions.

Previous work on sensorimotor adaptation mechanisms has demonstrated that it is necessary to compute implicitly a directional error by recognizing inconsistency between a reference axis in the applied coordinate system and the actual movement direction in pointing. A successful adaptation will be achieved by a reduction of the directional error through a realignment of the reference axis. Thus, the behavior will be adjusted progressively

(Krakauer, Pine, Ghilardi, & Ghez, 2000). For example, the diametrical cluster (i.e. direction 4 and 10) might form a kind of reference axis within skilled adapters’ cognitive representation of movement directions connecting left- and the rightward directions or left and right hemispheres, which makes it easier to adapt to a distortion in terms of a left–right reversal. The results of the experiments presented here demonstrate that matching the demands required in the adaptation task (i.e. mirroring along the sagittal axis) and the functionally related cognitive representations of movement directions (i.e. a global representation which is aligned to cardinal axes) is advantageous to adaptation performance.

Moreover, past research has shown that interference between different sensory distortions in adaptation tasks (i.e. force field and visuomotor rotation adaptation) led to observable performance errors if they address the same kinematic parameter (Tong, Wolpert, & Flanagan, 2002). These errors may be due to a representation of both distortions in one unique coordinate system. Our findings support the theory that a task-dependent cognitive representation can be accessed from memory, and therefore, a direction-sensitive cognitive representation will be applied in directional tasks. Thus, the structure of cognitive representations determines the performance level in sensorimotor adaptation tasks with similar kinematic distortions. If two different kinematic parameters want to access the identical cognitive representation structure (i.e. the representation of movement directions) to execute goal-directed movements in distinct directions, they will compete for the identical resource, which will lead to a decrease in actual performance.

It can be assumed from our findings that movement directions are represented in human memory in a distinct and individual manner, but the way the cognitive representation structure is applied under diverse conditions might vary. The cognitive representation of movement directions will be developed, activated, and applied in accordance with the executed motor task. Aside from the relevance of the accordance between the executed motor task and the relevant cognitive representation, it might be a chunking mechanism underlying the performance advantages in skilled adapters. Experiments investigating the learning of movement sequences (e.g. Panzer, Wilde, & Shea, 2006; Braden, Panzer, & Shea, 2008) showed that there is a decrease in response time when a movement sequence is reproduced. A reduction in response time found in trained experts (intervention group) is explained by the decreased duration of some, but not all elements being produced in the movement sequence. Thus, two or more elements of the movement sequence are chunked and allow the motor system to respond faster, because they are treated as relatively independent subsequences. A similar mechanism is detected in the current study. Expert performance in sensorimotor adaptation might rely on advantages achieved by a chunking of cardinal movement directions in the cognitive representation structure. These chunks allow a faster (i.e. in fewer trials) adaptation toward a distortion which is functionally similar according to their representation structure than is seen in a person whose structure does not classify the distortion as similar. For this reason, it may be easier for skilled adapters to develop necessary and adequate motor commands and achieve results, which are more similar to undistorted trials.

A global cognitive representation of movement directions appears to be advantageous to performance in the utilized adaptation task, whereas a local cognitive representation leads to a disadvantage in the same task. Theoretically, it can be hypothesized from our findings that having a local representation of movement directions (i.e. the clustering of neighboring movement directions without the prominent role of cardinal axes) may be beneficial in a sensorimotor adaptation task in which visual feedback is only rotated a few degrees (e.g. 30° clockwise or counterclockwise rotation). Still, further research is necessary to test this assumption, because it is also conceivable that a global representation of movement directions (i.e. clustering around the cardinal axes) generally facilitates sensorimotor adaptation and may still be more beneficial than a local representation, even under the aforementioned conditions.

The approach used in this study overcomes the traditional perspective of studying cognition and action separately. Our approach integrates the measurement of cognitive representations of movement directions in the research of sensorimotor control performance and helps to understand the involved cognitive mechanisms as suggested by Georgopoulos (2000). It can be summarized that the structure of cognitive representations concerning movement directions (the individualized cognitive categorization of movement directions) plays a critical role in sensorimotor adaptation tasks. This supports not only the argument that learning is mostly related to the development and change of cognitive structures in memory but, furthermore, that motor performance is based on an interaction between sensorimotor and cognitive systems (Schack & Ritter, 2009).

In summary, the present findings confirm the notion that sensorimotor adaptation performance is influenced by the structure of cognitive representations of movement directions, as a strategic control mechanism (see Redding & Wallace, 1996). If a global cognitive representation of movement directions is functionally related to the demands of a sensorimotor adaptation task (i.e. visuomotor distortion in terms of a mirroring along the sagittal axis), the adaptation performance will be facilitated. It is concluded that the structure of cognitive representations of movement directions can be seen as an indicator and a predictor for adaptation performance.

References

Abeele S, Bock O (2003) Transfer of sensorimotor adaptation between different movement categories. Exp Brain Res 148(1): 128–132

Bálint R (1909) Seelenlähmung des ‘‘Schauens,’’ optische Ataxie, räumliche Störung der Aufmerksamkeit (transl. Paralysis of visual perception). Monatszeitschrift PsychiatrNeurol 25:51–81

Battaglia-Mayer A, Caminiti R (2002) Optic ataxia as a result of the breakdown of the global tuning fields of parietal neurones. Brain 125:225–237

Battaglia-Mayer A, Mascaro M, Brunamonti E, Caminiti R (2005) The over-representation of contralateral space in parietal cortex: a positive image of directional motor components of neglect? Cereb Cortex 15(5):514–525

Bläsing B (2010) The dancer’s memory: expertise and cognitive structures in dance. In: Bla¨sing B, Puttke M, Schack T (eds) The neurocognition of dance. Psychology Press, London, pp 75–98 Bläsing B, Tenenbaum G, Schack T (2009) The cognitive structure of movements in classical dance. Psychol Sport Exerc 10(3): 350–360

Bock O (2005) Components of sensorimotor adaptation in young and elderly subjects. Exp Brain Res 160(2):259–263. doi:10.1007/s00221-004-2133-5

Bock O, Girgenrath M (2006) Relationship between sensorimotor adaptation and cognitive functions in younger and older subjects. Exp Brain Res 169(3):400–406

Braden HW, Panzer S, Shea CH (2008) The effects of sequence difficulty and practice on proportional and nonproportional transfer. Q J Exp Psychol 61(9):1321–1339

Caminiti R, Johnson PB, Urbano A (1990) Making arm movements within different parts of space: dynamic aspects in the primate motor cortex. J Neurosci 10(7):2039–2058

Caminiti R, Johnson PB, Galli C, Ferraina S, Burnod Y (1991) Making arm movements within different parts of space: the premotor and motor cortical representation of a coordinate system for reaching to visual targets. J Neurosci 11(5):1182–1197

Caminiti R, Chafee MV, Battaglia-Mayer A, Averbeck BB, Crowe DA, Georgopoulos AP (2010) Understanding the parietal lobe syndrome from a neurophysiological and evolutionary perspective. Eur J Neurosci 31(12):2320–2340

Georgopoulos AP (2000) Neural aspects of cognitive motor control. Curr Opin Neurobiol 10(2):238–241

Georgopoulos AP, Massey JT (1987) Cognitive spatial-motor processes. 1. The making of movements at various angles from a stimulus direction. Exp Brain Res 65(2):361–370

Georgopoulos AP, Kalaska JF, Massey JT (1981) Spatial trajectories and reaction-times of aimed movements—effects of practice, uncertainty, and change in target location. J Neurophysiol 46(4):725–743

Georgopoulos AP, Caminiti R, Kalaska JF, Massey JT (1983) Spatial coding of movement: a hypothesis concerning the coding of movement direction by motor cortical populations. Exp Brain Res Suppl 7:327–336

Georgopoulos AP, Schwartz AB, Kettner RE (1986) Neuronal population coding of movement direction. Science 233(4771): 1416–1419

Grigorova V, Petkova G, Bock O (2006) On the distribution of attention in a visuo-manual adaptation task. Exp Brain Res 175(4):754–757

Ingram HA, van Donkelaar P, Cole J, Vercher JL, Gauthier GM, Miall RC (2000) The role of proprioception and attention in a visuomotor adaptation task. Exp Brain Res 132(1):114–126

Kolb B, Whishaw IQ (1996) Fundamentals of human neuropsychology, 4th edn. W. H Freeman and Company, New York

Krakauer JW, Pine ZM, Ghilardi MF, Ghez C (2000) Learning of visuomotor transformations for vectorial planning of reaching trajectories. J Neurosci 20(23):8916–8924

Lacquaniti F, Guigon E, Bianchi L, Ferraina S, Caminiti R (1995) Representing spatial information for limb movement: role of area 5 in the monkey. Cereb Cortex 5(5):391–409

Maycock J, Dornbusch D, Elbrechter C, Haschke R, Schack T, Ritter H (2010) Approaching manual intelligence. KI-Ku¨nstliche Intelligenz 24:287–294

Mervis CB, Rosch E (1981) Categorization of natural objects. Annu Rev Psychol 32:89–115

Miall RC, Jenkinson N, Kulkarni K (2004) Adaptation to rotated visual feedback: a re-examination of motor interference. Exp Brain Res 154(2):201–210

Panzer S, Wilde H, Shea CH (2006) Learning of similar complex movement sequences: proactive and retroactive effects on learning. J Motor Behav 38(1):60–70

Paz R, Vaadia E (2009) Learning from learning: what can visuomotor adaptations tell us about the neuronal representation of movement? In: Sternad D (ed) Progress in motor control. Advances in experimental medicine and biology, vol 629. Springer, New York, pp 221–242

Pipereit K, Bock O, Vercher JL (2006) The contribution of proprioceptive feedback to sensorimotor adaptation. Exp Brain Res 174(1):45–52

Redding GM, Wallace B (1996) Adaptive spatial alignment and strategic perceptual-motor control. J Exp Psychol Hum Percept Perform 22(2):379–394

Schack T (2004) The cognitive architecture of complex movement. Int J Sport Exerc Psychol 2(4):403–438

Schack T (2011) Measuring mental representations. In: Tenenbaum G, Eklund RC, Kamata A (eds) Handbook of measurement in sport and exercise psychology, vol 1. Human Kinetics, Champaign

Schack T, Hackfort D (2007) Action-theory approach to applied sport psychology. In: Tenenbaum G, Eklund RC (eds) Handbook of sport psychology. Wiley, Hoboken, pp 332–351

Schack T, Mechsner F (2006) Representation of motor skills in human long-term memory. Neurosci Lett 91(3):77–81 Schack T, Ritter H (2009) The cognitive nature of action—functional links between cognitive psychology, movement science, and robotics. Prog Brain Res 174:231–250

Smyrnis N, Taira M, Ashe J, Georgopoulos AP (1992) Motor cortical activity in a memorized delay task. Exp Brain Res 92(1): 139–151

Stöckel T, Hughes CML, Schack T (2011) Representation of grasp postures and anticipatory motor planning in children. Psychol Res. doi:10.1007/s00426-011-0387-7

Tong C, Wolpert DM, Flanagan JR (2002) Kinematics and dynamics are not represented independently in motor working memory: evidence from an interference study. J Neurosci 22(3):1108–1113

van Beers RJ, Wolpert DM, Haggard P (2002) When feeling is more important than seeing in sensorimotor adaptation. Curr Biol 12(10):834–837

Weigelt M, Ahlmeyer T, Lex H, Schack T (2011) The cognitive representation of a throwing technique in judo experts—technological ways for individual skill diagnostics in high-performance sports. Psychol Sport Exerc 12(3):231–235

Wolpert DM, Ghahramani Z, Jordan MI (1995) An internal model for sensorimotor integration. Science 269(5232):1880–1882

Wu W, Hatsopoulos NG (2006) Evidence against a single coordinate system representation in the motor cortex. Exp Brain Res 175(2):197–210

Wu W, Hatsopoulos NG (2007) Coordinate system representations of movement direction in the premotor cortex. Exp Brain Res 176(4):652–657

Representations in Complex Actions

CHAPTER 4

Abstract The present study evaluates the cognitive representation of a kicking movement performed by a human and a humanoid robot, and how they are represented in experts and novices of soccer and robotics, respectively. To learn about the expertise-dependent development of memory structures, we compared the representation structures of soccer experts and robot experts concerning a human and humanoid robot kicking movement. We found different cognitive representation structures for both expertise groups under two different motor performance conditions (human vs. humanoid robot). In general, the expertise relies on the perceptual-motor knowledge of the human motor system. Thus, the soccer experts' cognitive representation of the humanoid robot movement is dominated by their representation of the corresponding human movement. Additionally, our results suggest that robot experts, in contrast to soccer experts, access functional features of the technical system of the humanoid robot in addition to their perceptual-motor knowledge about the human motor system. Thus, their perceptual-motor and neurofunctional machine representation are integrated into a cognitive representation of the humanoid robot movement.

This chapter is a revised version of Lex, H., Schütz, C., Knoblauch, A., & Schack, T. (2014). Cognitive Representation of a Complex Motor Action Executed by Different Motor Systems. Minds & Machines, *24*(3).

Introduction

For social interaction in general, one needs to single out relevant information from the steady stream of information influx to infer others' intentions and mental states and to coordinate one’s own action with the actions of other people based on specific representations (Knoblich & Jordan, 2003; Schack & Ritter, 2009). When humans have task-related interactions with one another (e.g., driving instructors teaching their students how to drive) both agents develop representations of the specific situations, the partner, and the task to be solved. However, it is yet to be studied how individual and shared mental models of environmental settings, motor actions, or task contexts are established in task-related interactions (Sebanz, Bekkering &, Knoblich 2006). The current study is designed to shed light on the question of how people engage in collaborative interactions with other humans and/or with robots, by investigating the underlying mental representations and how these can facilitate human-human and human-robot-interaction (HRI).

To gain a better understanding of representation and categorization in action and interaction, it is fundamental that researchers understand how movements are represented in long-term memory. It is hypothesed that human motor control requires that actions are planned and represented in terms of intended perceptual effects and that experts require a well-structured mental representation of the task in order to carry out their movements successfully (Jeannerod, 2001; Pulvermüller, 2005). A number of studies provided evidence that motor representations in humans not only integrate perceptual effects but furthermore encode biomechanical information (e.g., speed and velocity) of human motion (Knoblich & Prinz, 2001; Flach, Knoblich & Prinz, 2004; Schack, 2003).

Due to current advances in robotic technology, highly developed humanoid robots are able to perform manual and complex motor actions similar to humans. However, current robot control is largely focused on a very low level of abstraction that is closely focused on sensors and actuators. In contrast, human actions are strongly influenced by the knowledge about the characteristics of the manipulated objects, about action goals, and about disturbances and mishaps that usually occur during even moderately complex movements. Therefore, shaping the movements of advanced humanoid robots, or more ambitiously, shaping their interaction in the complex real-world environment, raises a substantial number of non-trivial research questions (Pfeiffer & Bongard, 2007; Schack & Ritter, 2009, 2013). One of these questions is concerned with humans’ cognitive representations of humanoid robot movements. Because of the significant differences in sensory and biomechanical organization between humans and humanoid robots, humans cannot represent the perceptual and biomechanical movement effects of the robots. Thus, it is unclear whether humans simulate robotic movements based on their own motor representation, or based on a technical understanding of humanoid robot movement production. In the first simulation, they preferably use their representation of the own motor system. In the second simulation, they preferably generate and use a neuro-functional machine representation. Until now, there is no trivial answer to that question.

It has been demonstrated that the motor execution of a simple arm movement is impaired while observing another human executing an incongruent arm movement. This is not the case when a humanoid robot motor system is executing the same incongruent arm movement instead (Kilner, Paulignan, & Blakemore, 2003). This finding indicates that the observation of a humanoid robot movement and the observation of a human movement are based on different representation structures. Thus, it can be speculated that interfering cognitive processes are influencing the perception and simulation of human and humanoid robot movements. Some of these mechanisms are simultaneously involved in the perception, simulation and execution of motor actions. The mechanism to observe movement intentions of other humans is based upon the functional equivalence of the cognitive representations involved in action execution, motor simulation, and action observation (Blakemore & Decety, 2001; Grezès & Decety, 2001). Thus, expert sport performance can be characterized by the advanced abilities and skills of athletes, in particular by the ability to predict other players' behavior (Ward & Williams, 2003).

Advanced basketball players, for instance, are able to predict the success of free throws earlier and more accurately than novices, and more accurately than people with comparable visual expertise (e.g., sports journalists). These differences are already observed for movement phases before the ball left the hand. Experts are able to interpret body kinematics more accurately and more easily. To this end, they develop sport-specific anticipatory mechanisms (i.e., perceptual resonance) that enables them to predict others' actions ahead of their realization (Aglioti, Cesari, Romani, & Urgesi, 2008). Hence, the understanding of observed actions results from a mechanism that maps an observed action onto existing representations of that action in observers' long-term memory (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Supporting evidence for this 'direct matching hypothesis' is provided by a study involving participants in a block stacking task under two different conditions. In the first condition, the participants only observed the blocks getting stacked, while in the second condition they executed the task by themselves. Interestingly, the eye movements were identical under both conditions. The authors concluded that the eye movements are controlled based on motor representations of the corresponding actions (Flanagan & Johansson, 2003). Thus, perception is controlled by motor representations even when a task is observed and not executed. Moreover, when athletes were shown similar movement patterns from classical ballet and Capoeira, activation in premotor and parietal areas was higher while observing the movements that corresponded to their area of expertise (i.e., classical ballet or Capoeira). Vice versa, the effect was much smaller when the perceived motor action did not belong to their area of expertise. This finding indicates that the observation of a movement initiates a covert simulation of the corresponding action (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Calvo-Merino, Grezes, Glaser, Passingham, & Haggard, 2006).

In general, it can be stated that humans are able to perceive the effects of motor actions executed by other humans based on their cognitive representation of that motor action. These cognitive representations help humans to interact in a proper way with other humans. The present study tries to elucidate the influence of the executing motor system (e.g., human or humanoid robot) on the corresponding cognitive representation. Specifically, we ask whether such cognitive representations are sensitive to the executing motor system, i.e., when a humanoid robot executes a comparable motor action instead of a human motor system. It is hypothesed that humans, when perceiving a humanoid robot movement, activate cognitive representation structures of the corresponding human movement related to their motor-system-specific expertise. Furthermore, we hypothesize that humans with a particular knowledge about either the motor system or the movement will activate all accessible knowledge.

Methods

Participants

Thirty-five participants (male, mean age 26.4 years, SD = 4.56) gave informed consent to participate in this study. The study was performed in accordance with the ethical standards described in the 1964 Declaration of Helsinki. Additionally, one high level expert (29 years old) from the field of soccer was investigated. This high-level expert was a former member of the German A - National Team.

The participants (N = 35) were subdivided in two groups according to their soccer-specific expertise. The first group (n = 18) consisted of experienced soccer players and served as experts for the human movement. They had on average a soccer experience of 17.53 years (SD = 3.12) with 9.31 hours (SD = 2.99) of organized training per week, and played in the fourth league (i.e., highest amateur level) in Germany. These participants had no experience in handling with a humanoid robot. The second group (n = 17) consisted of humans experienced in handling a humanoid robot platform. They worked with humanoid robots on average for 4.63 years (SD = 2.57) in a full time job at a scientific research institute. This group served as experts for the movement executed by humanoid robot model. They had on average a soccer experience of 2.12 years (SD = 2.49) received at non-organized leisure time activities or at school.

Stimuli

An instep kick from soccer was investigated in this study. This movement was chosen because both motor systems (human and humanoid robot) were able to execute it in a comparable manner. For example, the kicking movement of the humanoid robot is extensively used at soccer RoboCup competitions. The investigated humanoid robot platform was the NAO robot. The NAO robot is a humanoid robot platform built by Aldebaran Robotics. It has a 52 cm tall body integrating electric motors and actuators with 25 degrees of freedom. This humanoid robot is used at the RoboCup World Cup as the state-of-the-art technical platform. The human model was a soccer expert, and former player in the first Bundesliga (i.e., highest soccer division in Germany). He possessed a very good soccer specific demonstration technique.

To study the cognitive representation, the investigated movements were broken down into relevant Basic Action Concepts (BAC). BACs were defined in correspondence to the well-known conception of basic concepts in the field of object categorization described by Mervis & Rosch (1981). Recognizable movement features characterized BACs, and BACs were treated as functionally essential components of complex motor actions (Schack, 2011; Schack & Mechsner, 2006). Before the study commenced, an evaluation study was conducted to verify the relevant BACs. The pre-defined BACs for an instep kick in soccer were judged by experienced coaches (N = 5, holding at minimum an A-license from the Deutscher Fußball-Bund or the Union des Associations Européennes de Football). These coaches were asked to state how relevant all the described BACs were for an appropriate movement execution (in a percentage between 0 and 100, N = 25). The final set of most important BACs (n = 12) were defined based on an item fit analysis integrating the coefficient of variation. An overview of the used BACs and the item fit analysis is provided in Table 4.1.

Table 4.1

Overview of used BACs.

Short phrases characterize the nature of the cognitive units used in the experiment. The calculation of an item fit for each stimulus based on coaches' decisions and formed the basis to choose for the 12 most relevant out of 25 adequate BACs for the instep kick in soccer applied in the experiment. BACs 1 to 4 describe the assisting phase (preparation), BACs 5 – 9 describe the main phase (kicking), and BACs 10 – 12 the assisting phase (follow through).

No	Description of BAC	Mean	SD	Item fit
1	look to the ball	88.00	21.68	63.36
2	upper body leans forward	86.00	15.17	68.37
3	bend knee of the supporting leg	72.00	20.49	43.54
4	foot of the supporting leg points towards kicking direction	82.00	10.95	68.64
5	Kicking leg swings in kicking direction	90.00	10.00	78.89
6	acceleration of the lower leg	87.00	12.04	73.16
7	toehold points straight downward	94.00	08.94	84.48
8	knee of the kicking leg is above the ball	72.00	16.43	49.18
9	meet the ball with instep at the center	94.00	08.94	84.48
10	no hyperextension of the knee	72.00	23.87	38.84
11	gaze follows the ball trajectory	66.00	31.30	18.57
12	kicking leg swings through	62.00	16.43	35.50

The BACs were depicted as static images. Thus, the images served as stimuli in the experiment. Figure 4.1 presents the static images of BAC 9 for the human and the humanoid robot movement.

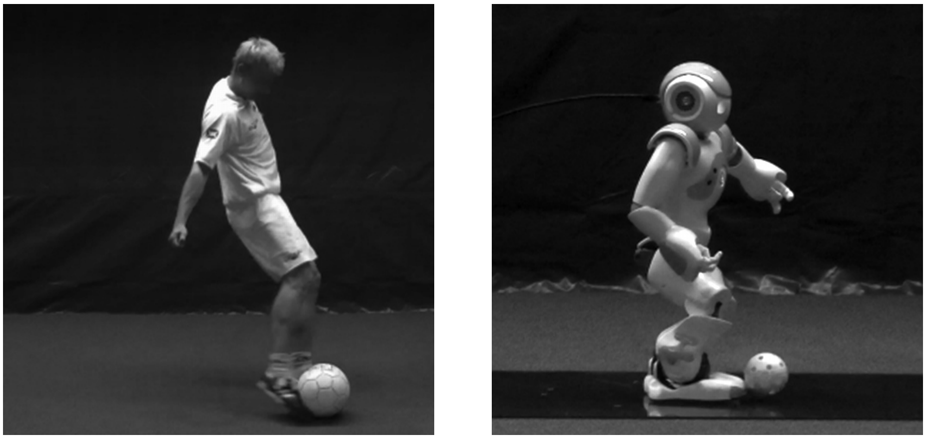

Figure 4.1 BAC 9 describing the most important BACs in the execution of the instep kick in soccer for humans (left) and humanoid robots (NAO, right). Participants were confronted with similar static pictures taken out of the identical movement. All stimuli were matched regarding their visual appearance of both models (i.e., both models were dressed in white in front of a dark same-colored background). Both stimulus sets were aligned to match the models in size.

Task & Procedure

To analyze the cognitive representation of the participants for both movements, the Structural-Dimensional Analysis of Mental Representations (SDA-M; Schack, 2004, 2011) was applied. The SDA-M measured the cognitive representation of the movement (executed once by the human and once by the humanoid motor system) with the corresponding BACs described in Table 4.1 in two separate experiments. The order of both experiments was counter-balanced across participants in each group.

Both experiments were conducted in the identical manner except the stimuli were aligned to the corresponding movement. Participants had to perform a splitting procedure. Two BACs were presented on the screen simultaneously. The BAC presented in the upper position was in an anchoring position. Participants were asked: Please decide whether the BAC presented in the lower position is similar to the BAC in the anchoring position during movement execution. To answer that question the participants were implicitly requested to determine a similarity criterion from their own memory (i.e., referring to their own knowledge base about that movement). If both BACs were related to each other during movement execution, participants sorted the BAC in the lower position into a positive subset. If not, they sorted it into a negative subset. Afterwards, the next BAC was presented in the lower position and again compared to the BAC in the anchoring position. When all decisions related to the BAC in the anchoring position were made, the next randomly chosen BAC was presented in the anchoring position. This process was repeated until every BAC was once in the anchoring position and, thus, had been compared with every other BAC.

Data analysis

The SDA-M consists of three analysis steps: In the first step, the described splitting procedure reveals the proximity between the BACs for each movement separately. The splitting procedure results in a positive and a negative subset for each BAC in the anchoring position. The BACs sorted into the subsets are assigned a score, which reflects their similarity to the BAC in the anchoring position. The sign of the subset (positive/negative) and the number of elements within each subset form the basis for that score. This procedure results in a score vector for each BAC in the anchoring position. The concatenation of all score vectors creates a matrix in which each row corresponds to one BAC. The rows are then converted to a relative position of each

BAC in multidimensional space by a z-normalization. From this normalized position matrix, a Euclidian distance matrix is calculated.

In the second step, the cognitive representations of the kicking movements (i.e., executed by the human and humanoid motor system) are calculated by applying an unweighted average-linkage hierarchical cluster analysis to the Euclidean distance matrix. The cluster analysis results in a dendrogram (e.g., Figure 4.2). The Euclidean distance between a given pair of BACs can be read as the height of each conjunction on the y-axis. The smaller the Euclidean distance between BACs, the more similar the participants perceive the BACs, and the closer they are represented in the participants' long-term memory. Based on an error probability of $p = .01$, a critical Euclidean distance with a value of $d_{crit} = 4.55$ was calculated. All BACs connected below this critical value belong to a common cluster. By contrast, BACs connected above the critical value belong to statistically distinct clusters.

In the third step, the measure of invariance λ is calculated between dendrograms in order to test the generated representation structures for structural homogeneity. The measure of invariance value λ ranges between 0 and 1, whereas 1 indicates the highest accordance between two structures. The statistical threshold for accepting invariance between two structures is set to $\lambda = .68$ (Lex, Weigelt, Knoblauch, & Schack, 2012; Schack, 2004).

Results

Figure 4.2 illustrates the cognitive representation of the high-level soccer player. The cognitive representation of this expert for the human movement is comparable to the phase description of the instep kick in soccer (Lees & Nolan, 1998). The cognitive representation consists of three distinct clusters. The first cluster (1 - 4) indicates an assisting phase (the preparation). The second cluster (5 - 9) indicates the main phase (kicking the ball), and the third cluster (10 - 12) is an additional assisting phase (follow trough). The single soccer experts' cognitive representation of the human movement is functionally aligned to relevant phases of the movement execution. That representation structure reveals a highly automated and internalized cognitive representation of the human kick movement.

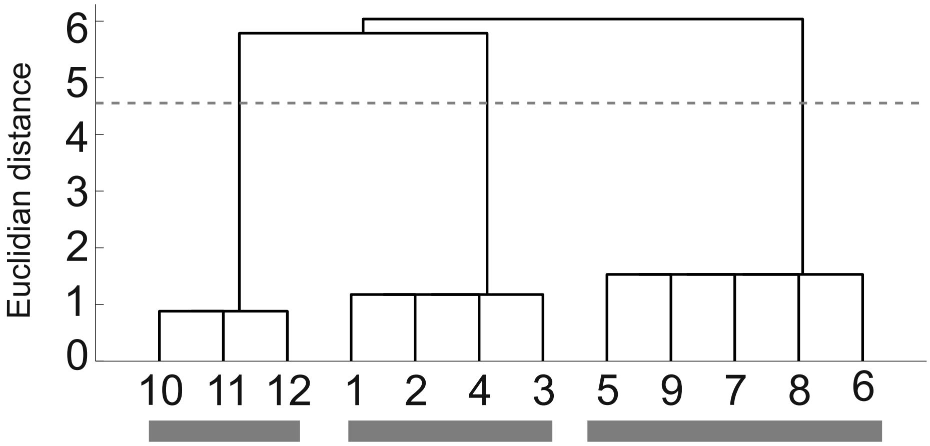

Figure 4.2 The cognitive representation of the high level expert in soccer for the human movement. The numbers at the bottom refer to the BACs of the movement. The numbers at the y-axis refer to the Euclidian distances between the connected BACs. The grey dashed line signifies the critical Euclidean distance (d_{crit}) where all branches of the dendrogram were cut off. Everything connected to one branch below this value forms a common cluster. The solid grey bars at the bottom of the dendrogram indicate the emerged clusters.

The average cognitive representation, split by expertise (robot/soccer experts) and model (human/humanoid robot) are illustrated in

Figure 4.3. The soccer experts' cognitive representation of the human movement (Figure 4.3a) is structurally identical to the cognitive representation of the single high-level expert (Figure 4.2), λ = 1.0. This representation structure is aligned to the functional demands of the movement execution for a kicking movement in soccer. The robot experts' cognitive representation of the human movement (Figure 4.3c) is structurally dissimilar to the high-level expert (Figure 4.2, λ = 0.57), and consists of four particular clusters. The preparation phase of the movement is divided into two separate subphases. The robot experts' representation of the human movement shows an alignment towards the ball as a separate phase (1 - 2), and a separate cluster for the definition of the kicking direction combined with the shooting power (3 - 4). Nevertheless, the third cluster (5 - 9) as well as the fourth cluster (10 - 12) indicate a functional organization of the human movement. The soccer experts' cognitive representation of the humanoid robot movement (Figure 4.3b) consists of three clusters and one singled BAC (8). A first assisting movement phase indicates the alignment to the ball (1 – 2). A second assisting phase (3 – 7) describes the movement preparation. One specificity is the singled BAC 8 (i.e., knee of the kicking leg is above the ball). The last cluster (9 – 12) indicates the main movement phase (kicking the ball) together with the follow through phase within the humanoid robot movement. This representation structure is statistically different compared to the soccer experts' representation of the human movement, λ = 0.57. The robot experts' cognitive representation of the humanoid robot movement (Figure 4.3d) is statistically different to their representation of the human movement (λ = 0.55), and to the soccer experts' cognitive representation of the humanoid robot movement (λ = 0.51). Four clusters designate the robot experts' cognitive representation of the humanoid robot movement. The first

cluster (1 - 2) describes an assisting movement phase (alignment to the ball). The second cluster (3 - 6) indicates the movement preparation with the shifting of the weight towards the supporting leg. Cluster three (7 - 8) consists of the movement components which are related to the movement execution of the kicking leg. The fourth cluster (9 - 12) is integrating all movement components from the first contact with the ball until the end of the movement, including the follow through. Table 4.2 summarizes the results of the comparison of evolved cluster structures.

Table 4.2

Comparison of similarity between the groups (soccer/robot experts) for both motor systems (human/ humanoid robot model). The λ value is supposed to be between 0 (no similarity between the cluster structures) and 1.0 (identical cluster structures). Two cluster structures are regarded as similar to each other when λ > 0.68.

Group 1	Group 2	λ value
high level expert – human model	soccer experts – human model	1.00
high level expert – human model	robot experts – human model	0.57
soccer experts – human model	soccer experts – humanoid robot model	0.57
robot experts – human model	robot experts – humanoid robot model	0.55
robot experts – humanoid robot model	soccer experts – humanoid robot model	0.51

A last analytic step investigated the average cognitive representation over all participants for both movements. Figure 4.4a illustrates the average cognitive representation of the human movement over all participants, which shows three distinct clusters. Cluster one (1 - 4) indicates the assisting phase (preparation). The second cluster (5 - 9) indicates the main phase (kicking the ball), and the third cluster (10 - 12) the assisting phase (follow trough).

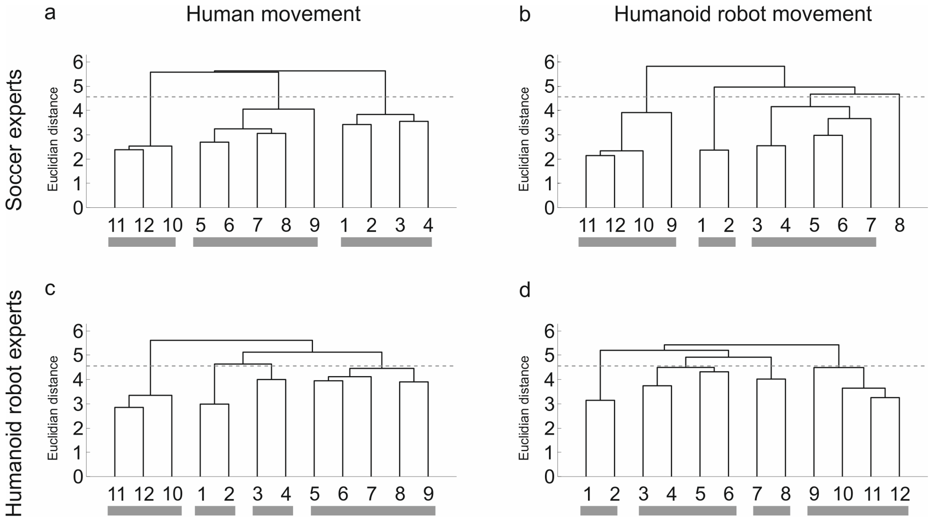

Figure 4.3 Cognitive representation structures for the soccer experts of the human (a) and the humanoid robot (b) movement, as well as the cognitive representation structures for the robot experts of the human (c) and the humanoid robot (d) movement. The numbers at the bottom and at the y-axes are identical to Figure 4.2.

This representation structure is identical (λ = 1.0) to the cognitive representation of the soccer experts (Figure 4.3a) and the single soccer experts' cognitive representation (Figure 4.2) of the human movement. Figure 4.4b illustrates all participants’ cognitive representation of the humanoid robot movement indicating four distinct clusters. Cluster one (1 – 2) is representing the alignment of the humanoid robot towards the ball. The second cluster (3 – 6) is best be described by the backward movement of the kicking leg. The third cluster (7 – 8) focuses on the movement features of the kicking leg and their relevance for the movement execution. The main phase (9 – 12) combines the kicking of the ball with the movement parameters of the follow through (assisting phase). All participants' cognitive representation of the humanoid movement is statistically different to all participants’ cognitive representation of the human movement, λ = 0.47. Further, all participants’ cognitive representation of the human movement is identical to the soccer experts’ cognitive representation of the human movement, λ = 1.0. Additionally, all participants’ cognitive representation of the humanoid robot movement is identical to the robot experts’ cognitive representation of the humanoid robot movement, λ = 1.0.

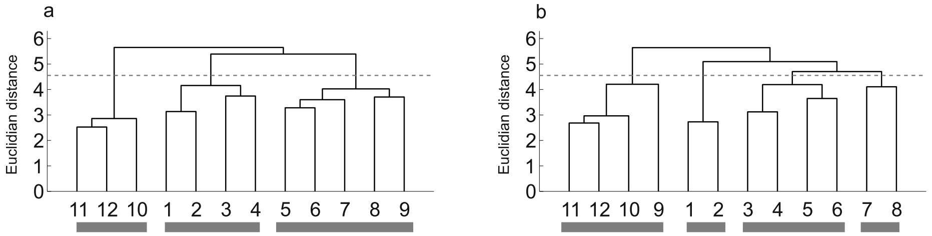

Figure 4.4 All participants’ cognitive representation of the human (a) and the humanoid robot (b) movement.

Discussion

The present study was designed to investigate the cognitive representation of a kicking movement executed by a human and a humanoid robot. The comparative performance of two groups was examined – a group of soccer experts and a group of humanoid robot experts. The implications of the results of the experiments are discussed with regard to certain fields of expertise of both groups, and with regard to a global perspective involving implications regarding cognitive representations in humans.

We asked whether humans would activate their own, movement-specific knowledge structures to understand the intended goals of an action while perceiving a humanoid robot performing a movement. The data of the current study supports this hypothesis. However, the activated representation structures are shaped differently based on the knowledge background of the observer. Three observations in this study support this assumption. First, the results showed a functionally organized cognitive representation of the human movement for the single high-level expert in soccer. In comparison to studies from tennis (Schack & Mechsner, 2006), dancing (Bläsing, Tenenbaum, & Schack, 2006), or judo (Weigelt, Ahlmeyer, Lex, & Schack, 2011), additional evidence was delivered that the memory structure of a high-level expert is functionally organized. As well as the level of expertise (i.e., a certain league), the domain-specific experience (i.e., years of practice) contributes to an establishment of functionally organized cognitive representations (Ericsson, Krampe, & Tesch-Römer, 1993). Thus, the representation structures between the single soccer expert and the group of soccer experts were statistically identical.

In contrast, robot experts' cognitive representation of the human movement was statistically different to the soccer experts. This difference is mostly related to the "preparation phase" of the kicking movement. The robot experts split the assisting phase into two subphases, which is dysfunctional with regard to the execution of the kicking movement. Remarkably, a comparable splitting of the "preparation phase" is found in robot experts' cognitive representation of the humanoid robot movement. This result indicates that the initiation of the kicking movement might be impaired in the robot experts. Nevertheless, their representation structure showed similarities regarding the main movement phases of "kicking the ball" and "follow through". This might be explained by the fact that the robot experts possess an extensive movement relevant experience with their own human motor system. It can be assumed that such a simple kicking movement is executed and experienced by almost every human. Interestingly, the cognitive representation of the humanoid robot movement shares common features between both expertise groups (e.g., the movement organization of the kicking phase for the BACs 9 – 12). This finding supports the idea that both groups try to access their knowledge about their own human motor system. They apply their perceptual-motor knowledge about the human movement (i.e., arm position, hip angle, etc.) to the humanoid robot movement, and therefore to the humanoid robot motor system. However, statistical differences have been observed (e.g., regarding the movement organization for the assisting phases for the BACs 3 – 8) between the cognitive representations of the human and the humanoid robot movement within both groups. The soccer experts' cognitive representations of the human and humanoid robot movement showed a difference regarding BAC 8, which was singled out. BAC 8 (knee of the kicking leg is above the ball) is responsible for a steady and flat ball trajectory within a human kicking movement. One may speculate that, to soccer experts, it seems impossible that a humanoid robot can execute this movement in a comparable fashion and play, for instance, a long ball in the air. Therefore, soccer experts might not have integrated such a BAC into the movement phases of the humanoid robot movement. In addition, the assisting phase, "movement preparation," was subdivided into two phases: BACs 1 – 2 and BACs 3 – 7. BAC 1 – 2 represented an assisting phase, which seems typical for humanoid robot movements. Thus, humans are unable to represent perceptual effects of humanoid robot movements. The movement phase (BACs 1 – 2) is observable within the robot experts' representation of the humanoid robot movement. The movement phase integrating the BACs 3 – 7 can be interpreted as directly associated with the preparation of the movement itself. Thus, movement phase one (BAC 1 – 2) represents the alignment of the body (i.e., meaning to be at the right place), and movement phase two (BACs 3 – 7) represents the specification of the lower limbs directly responsible for movement execution.

The robot experts' cognitive representations of the human and humanoid robot movement showed the largest differences regarding the representation of the BACs 3 – 8. The assisting phase (BACs 1 – 2, alignment of the body) is identical in the representation structure of both movements. It seems that robot experts start both movements with the alignment of the executing body towards the ball. However, they then separated the movement preparation into two phases. Phase one (BACs 3 – 6) seems to be representing the preparation of the essential movement-relevant specifications for the motor execution. In contrast, the BACs 7 – 8 seemed to be of marginal relevance for the movement execution. It can be speculated that the

BAC 7 and BAC 8 are controlled passively during the motor execution of the NAO robot.

The present data supports the hypothesis that humans activate cognitive representation structures if they perceive a humanoid robot movement. Both expertise groups (i.e., soccer and robot experts) try to apply their existing knowledge to different motor systems. The data suggests that the transferable knowledge differs between both groups. It can be assumed that soccer experts refer to their perceptual-motor knowledge about the execution of the human movement, and transfer their motor system representation onto the humanoid robot. Additionally, it can be assumed that robot experts activate their perceptual-motor knowledge of the human movement as well. However, they also access their representation of functional features of the humanoid technical system (i.e., functioning of the actuators within that humanoid robot). Their memory structure can be described as a neuro-functional machine representation. Of course, some researcher’s state that perceptual-motor skills and intellectual skills are "... as far apart, one might say, as gym lockers and libraries in a typical university" (Rosenbaum, Carlson, & Gilmore, 2001, p. 456). However, intellectual skills like the visual-spatial representation of a movement output (e.g., writing a word) can be generalized to untrained body parts such as writing with a foot (Meulenbroek, Rosenbaum, Thomassen, Loukopoulos, & Vaughan, 1996). The general adjustability (Abeele & Bock, 2003) between different sensorimotor adaptation tasks (i.e., transfer of intellectual knowledge about a distortion of the visual feedback from a pointing to a tracking task) delivers additional evidence that knowledge about task-specific features is combined with perceptual-motor knowledge. Thus, the robot experts’ cognitive representation of the humanoid movement indicated how functional features of technical systems (i.e., knowledge about the operation mode of a humanoid robot) are involved in the structure formation of cognitive representations. Additional evidence is delivered by the mean representation structure of all participants for the human and the humanoid movement. Humans tend to integrate all knowledge resources about the humanoid motor system that are accessible. Thus, perceptual-motor knowledge about the own motor system and functional features of the technical system are merged to create a cognitive representation of a humanoid robot movement. Furthermore, it can be speculated with regard to the described findings of Kilner, Paulignan, and Blakemore (2003) that this kind of cognitive representation might influence the corresponding motor behavior. In contrast to the described findings of Calvo-Merino, Glaser, Grezes, Passingham, & Haggard (2005), the perceptual-motor knowledge of the human motor system is to some extent transferable onto a humanoid robot motor system. However, knowledge about the functional features of the technical system complement the perceptual-motor knowledge of the human motor system.

Despite the fact that the dynamic systems approach (Gibson, 1977) and the motor approach (Schmidt & Lee, 2005) are fundamental research areas in motor control, the cognitive architecture of complex motor action also plays an important role in the understanding of movement organization (Schack & Ritter, 2013). Our results deliver further evidence in how far intellectual and motor-perceptual knowledge are integrated into the memory structure of a movement, and that both information resources have an impact on the integral cognitive structure formation. Thus, multiplexed experience in executing a specific motor action and in handling a humanoid agent might help humans to predict, interpret, and understand an observed motor action of a humanoid robot.

Finally, we would like to speculate about the integration of intellectual knowledge into a complex architecture of motor actions. This integration seems possible when a minimal perceptual-motor knowledge of the motor action is already established. We believe that further intellectual knowledge about actuators of a humanoid robot settles on an information base of the actual motor behavior. Such an information base is established as a cognitive representation integrating sensory potentials and produced environmental effects (Schack, 2004). An effect-oriented storage of complex motor actions is assumed to consist of different sensory input signals (kinesthetic, visual, auditory, etc.) which are aligned to Basic Action Concepts. The corresponding internal model stores and combines all possible redundant multisensory information (Schack, Bläsing, Hughes, Flash, & Schilling, 2014). Our results suggest that the intellectual knowledge about a motor system seems to be integrated into the corresponding internal model of a complex motor action as well. Thus, if humans have already built up a meaningful cognitive representation, they are able to integrate additional intellectual knowledge on subsequent organizational levels.

Presumably, a more intuitive interaction with humanoid robots would require the user to possess intellectual knowledge about their functionalities. Once this knowledge is acquired, the handling might become easier because the humanoid behavior becomes predictable and the understanding of a humanoid movement becomes more intuitive. However, such intellectual knowledge would not activate the specific action representations for human movements while perceiving a robot action. To this end, the robot would have to produce perceptual and biomechanical effects identical to the effects produced by humans (Press, 2011). In addition to Press (2011), it can be stated that the produced environmental effects and the intellectual knowledge about an observed agent mainly influence the tuning of an action observation network. Thus, street performers showing a Robo-Dance routine can be sure to catch the attention of the crowd, simply by pointing at the mismatch between the performed motor actions and the motor potential of the performing motor system. To overcome such mismatches in humanoid robot design we need to engineer bio-inspired machines making it easier for humans to understand the intended action goals of such machines. However, Pfeifer, Lungarella, and Iida (2007) pointed out, it is still a long way to go to engineer bio-inspired machines for the real world, and a lot research is necessary to strengthen such bold claims.

References

Abeele, S., & Bock, O. (2003). Transfer of sensorimotor adaptation between different movement categories. Experimental Brain Research, 148(1), 128-132.

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. Nature Neuroscience, 11(9), 1109-1116. doi:10.1038/nn.2182

Blakemore, S. J., & Decety, J. (2001). From the perception of action to the understanding of intention. Nature Reviews. Neuroscience, 2(8), 561-567.

Bläsing, B., Tenenbaum, G., & Schack, T. (2009). The cognitive structure of movements in classical dance. Psychology of Sport and Exercise, 10(3), 350-360.

Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. Cerebral Cortex, 15(8), 1243-1249.

Calvo-Merino, B., Grezes, J., Glaser, D. E., Passingham, R. E., & Haggard, P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. Current Biology, 16(22), 1905-1910. doi:10.1016/j.cub.2006.07.065

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. Psychological Review, 100(3), 363-406. doi:10.1037/0033-295X.100.3.363

Flach, R., Knoblich, G., & Prinz, W. (2004). Recognizing one's own clapping: the role of temporal cues. Psychological Research, 69(1-2), 147-156. doi:10.1007/s00426-003-0165-2

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. Nature, 424(6950), 769-771.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. Brain, 119, 593-609.

Gibson, J. J. (1977). The theory of affordances. In R. Shaw, & J. Bransford (Eds.), Perceiving, acting, and knowing: Toward an ecological psychology (pp. 67–82). Hillsdale, NJ: Erlbaum.

Grezès, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: A meta-analysis. Human Brain Mapping, 12(1), 1-19.

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. Neuroimage, 14(1), 103-109. doi:10.1006/nimg.2001.0832

Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An interference effect of observed biological movement on action. Current biology, 13(6), 522-525.

Knoblich, G., & Jordan, J. S. (2003). Action coordination in groups and individuals: learning anticipatory control. Journal of experimental psychology Learning, memory, and cognition, 29(5), 1006-1016. doi:10.1037/0278-7393.29.5.1006

Knoblich, G., & Prinz, W. (2001). Recognition of self-generated actions from kinematic displays of drawing. Journal of experimental psychology Human perception and performance, 27(2), 456-465. doi:10.1037/0096-1523.27.2.456

Lees, A., & Nolan, L. (1998). The biomechanics of soccer: A review. Journal of Sport Science, 16(3), 211-234.

Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2012). Functional relationship between cognitive representations of movement directions and visuomotor adaptation performance. Experimental Brain Research, 223(4), 457-467.

Meulenbroek, R. G., Rosenbaum, D. A., Thomassen, A. J., Loukopoulos, L. D., & Vaughan, J. (1996). Adaptation of a reaching model to handwriting: how different effectors can produce the same written output, and other results. Psychological Research, 59(1), 64-74.

Mervis, C. B., & Rosch, E. (1981). Categorization of natural objects. Annual Review of Psychology, 32, 89-115. doi:10.1146/annurev.ps.32.020181.000513

Pfeifer, R., & Bongard, J. (2007). How the body shapes the way we think: A new view of intelligence. Cambidge: The MIT Press.

Pfeifer, R., Lungarella, M., & Iida, F. (2007). Self-organization, embodiment, and biologically inspired robotics. Science (New York, N Y), 318(5853), 1088-1093.

Press, C. (2011). Action observation and robotic agents: learning and anthropomorphism. Neuroscience and Biobehavioral Reviews, 35(6), 1410-1418.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. Nature Reviews. Neuroscience, 6(7), 576-582. doi:nrn1706 [pii]10.1038/nrn1706

Rosenbaum, D. A., Carlson, R. A., & Gilmore, R. O. (2001). Acquisition of intellectual and perceptual-motor skills. Annual Review of Psychology, 52, 453-470.

Schack, T. (2003). The relationship between motor representation and biomechanical parameters in complex movements: Towards an integrative perspective of movement science. European Journal of Sport Science, 3(2), 1-13. doi:10.1080/17461390300073201

Schack, T. (2004). The cognitive architecture of complex movement. International Journal of Sport and Exercise Psychology, 2(4), 403-438.

Schack, T. (2011). Measuring mental representations. In G. Tenenbaum, R. C. Eklund & A. Kamata (Eds.), Handbook of Measurement in Sport and Exercise Psychology (Vol. 1). Champaign, Illinois: Human Kinetics.

Schack, T., Bläsing, B., Hughes, C., Flash, T., & Schilling, M. (2014). Elements and construction of motor control. In: A.G. Papaioannou & D. Hackfort (Eds.). Routledge Companion to Sport and Exercise Psychology: Global perspectives and fundamental concepts, p.308-323.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. Neuroscience Letters, 391(3), 77-81. doi:10.1016/j.neulet.2005.10.009

Schack, T., & Ritter, H. (2009). The cognitive nature of action - Functional links between cognitive psychology, movement science, and robotics. Progress in Brain Research, 174, 231-250. doi:10.1016/S0079-6123(09)01319-3

Schack, T. & Ritter, H. (2013). Representation and learning in motor action – Bridges between experimental research and cognitive robotics. New Ideas in Psychology, 31(3), 258-269. doi: 10.1016/j.newideapsych.2013.04.003

Schmidt, R. A., & Lee, T. D. (2005). Motor control and learning: A behavioral emphasis. Champaign, IL: Human Kinetics.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: bodies and minds moving together. Trends in cognitive sciences, 10(2), 70-76. doi:10.1016/j.tics.2005.12.009

Ward, P., & Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: The multidimensional nature of expert performance. Journal of Sport & Exercise Psychology, 25(1), 93-111.

Weigelt, M., Ahlmeyer, T., Lex, H., & Schack, T. (2011). The cognitive representation of a throwing technique in judo experts - Technological ways for individual skill diagnostics in high-performance sports. Psychology of Sport and Exercise, 12(3), 231 - 235.

Representations in Interactions

CHAPTER 5

Abstract Two core elements for the coordination of different actions in sport are tactical information and knowledge about tactical situations. In the present research, two experiments were conducted to learn about the memory structure and the cognitive processing of tactical information. Experiment 1 investigated the storage and structuring of team-specific tactics in humans' long-term memory with regard to different expertise levels. Experiment 2, in presenting participants the identical match situations in a reaction time task, was designed to investigate tactical decision-making skills and the corresponding gaze behavior. The results showed that more experienced soccer players, in contrast to less experienced soccer players, possess a functionally organized cognitive representation of team-specific tactics in soccer. Moreover, the more experienced soccer players reacted faster in tactical decisions, because they needed less fixations of similar duration as compared to less experienced soccer players. Combined, these experiments offer evidence that a functionally organized memory structure leads to a reaction time and a perceptual advantage in tactical decision-making in soccer. The results are discussed with regard to theoretical and practical implications.

This chapter is a revised version of Lex, H., Essig, K., Knoblauch, A., & Schack, T. (under revision). Cognitive Representations and Cognitive Processing of Team-Specific Tactics in Soccer. *PLoS ONE*.

Introduction

Skilled soccer players should be able to recognize and evaluate the potential opportunities and risks of actions quickly to react properly (Wein, 2007). In other words, if a soccer player employs an elaborate technique in controlling the ball (i.e., he possesses a proper action pattern), but is not able to apply this technical skill in an appropriate way, he becomes an almost "useless player" (Knapp, 1977). Therefore, tactical skills can be described as the ability of certain players to judge and decide for upcoming game situations appropriately (Gréhaigne & Godbout, 1995), and cognitive abilities, like the knowledge about different passing options or other tactical features of the game are a fundamental element of soccer playing competence. Moreover, tactical knowledge does not just facilitate information processing, but also more generally permits a target-related and purposeful adaptation of behavioral potentials to conditions in the environment (Ali, 2011). Therefore, it is necessary to access and store all relevant information and outcomes of the learning processes in tactical team cooperation as information in long-term memory (Williams & Reilly, 2000). Thus, an athlete's performance on the pitch not only involves knowledge about task-specific information, but also a learning-dependent modification of information. The present study was designed to investigate differences in the cognitive representation structures and in the cognitive processing of team-specific tactics in soccer.

Despite the fact that tactical skills related to sports performance in ball sports are difficult to access, they have become a fundamental research area. Different tests from psychological research have been applied in soccer to enhance knowledge about selected cognitive abilities of soccer-experienced individuals. For instance, the influence of a soccer skill test (Loughborough Intermittent Shuttle Test) on the mental concentration of soccer players has been investigated. The mental concentration task contained the identification of numbers between 1 and 100 in an ascending order from a randomized grid. The authors found that the mental concentration test performance itself did not differ between pre- and post-exercise trials (McGregor, Nicholas, Lakomy, & Williams, 1999). Thus, this kind of mental test has been applied with moderate success to investigate soccer-specific cognitive skills and athlete abilities, although these authors focused more on the effects of fluid consumption during soccer.

Additionally, Stroop Color and Word Tests were used to access team sport players' cognitive functions by evaluating an interference score which reflected participants' abilities to resist cognitive interference induced by the name of a color (e.g., "blue") and the visual color of a word (e.g., blue text). In this study, both the color and word scores of team sport players were higher during halftime in comparison to the identical pre-competition test. This elevated halftime score remained constant until the end of the match (Winnick et al, 2005). Thus, there is evidence that a demanding physical activity leads to a decrease in performance of the cognitive system. This test delivers insights into people's inhibitory control, which might be relevant to individual decision-making tactics in soccer. Importantly, the transfer of such abilities to team-specific tactics needs to be further investigated, because the ecological validity of this test as it relates to the structure of team-specific tactics in one's long-term memory can be questioned, but remains a fruitful research path.

Another tool with a better ecological validity is the observation and evaluation of soccer matches by video analysis. Early attempts to evaluate tactical behavior in soccer were conducted through observation of structured video scenes in which the position of team members on the pitch had to be recalled once the match situation was stopped and the screen was occluded. It was found that less experienced soccer players showed greater recall error of player positions in structured video scenes than more experienced soccer players (Williams, Davids, Burwitz, & Williams, 1993). The authors assumed that more experienced soccer players would be able to build up meaningful associations of the perceived player positions on the pitch in terms of their tactical goal. Thus, it was expected that the more experienced players benefitted from their ability to build up chunks of corresponding information. In line with these findings, it was speculated that passing options in soccer could be detected and evaluated better by more experienced soccer players. They are able to anticipate subsequent match options. Results revealed that soccer experts are more successful at anticipating possible passing destinations, because they access contextual information about what happens next and integrate that knowledge already stored in their memory (Ward & Williams, 2003). Moreover, video analysis techniques applied to soccer are often related to questions regarding the tactical behavior and performance-relevant indicators of the own and the opposing team (Carling, Williams, & Reilly, 2005; Memmert, 2004, 2006) aiming at the adjustment of the own team’s behavior. It makes the own team aware of repeating game openings, patterns to create shots on goal, or key players in opponent’s playmaking. Importantly, however, the results of such applied video analysis systems fail to deliver useful information about the cognitive representation structure, the cognitive processing, and the visual information processing of tactics in soccer (Garganta,2009).

A preferable approach to the investigation of cognitive structures of team-specific tactics is conducted by verbal protocol analysis during recall and recognition tests. Specifically, the evaluation of the verbal reports of thinking (i.e., non-structured protocols expressed verbally after the observation of match situations) indicate that more advanced cognitive representations enable more experienced players to retrieve relevant information in order to make appropriate task-specific judgments (Roca, Ford, McRobert, & Williams, 2011). There is evidence that expert sport performance is mediated by different structure formations in experts' long-term memory. A drawback of methods like the verbal protocol analysis is the uncertainty about what is exactly measured in the demanding environment in sport competition. Verbal protocols often refer to self-analyses, judgments, or wishes, rather than explicit knowledge or cognitive representations in long-term memory (Hodges, Huys, & Starkes, 2007).

Additionally, one can speculate about the organization of long-term memory structures, emphasizing the run of play in sport competitions. One reasonable hypothesis considered a conceptual organization of such run of play structures in the long-term memory in terms of 'tactical skills' (McPherson & Kernodle, 2003). These tactical skills were closely related to representations of tactical problems occurring during sport competitions. It was found that experts, when compared to novice athletes, possess "… more sophisticated conceptual networks of declarative and procedural knowledge (both tactical and motor skill related); procedures for response selection and execution; and specific memory adaptations and structures (e.g., sport specific strategies, situation profiles) that were stored and accessible from LTM" (McPherson & Vickers, 2004, p.277).

Furthermore, an approach called *Tactical Skills Inventory for Sports* assessed selected cognitive skills, like positioning and deciding, knowing about ball actions, etc. (Elferink-Gemser, Visscher, Richart, & Lemmink, 2004). That inventory (i.e., in form of a questionnaire) delivered insights regarding the cognitive processing of a few tactical parameters in soccer, which were not related to match strategy. The internal consistency, test-retest reliability, and construct validity was within an acceptable range; however, the integration of the observed tactical parameters towards the choice of players for a particular tactic was missing. Additionally, some authors verified a relation between executive functions and the tactical behavior of Under-15 soccer players Gonzaga, Albuquerque, Malloy-Diniz, Greco, and da Costa (2014). They found differences between low and high performers with regard to the tactical behavior in relation to their affective decision-making skills. The remaining question focusses on the factors responsible for such behavioral differences.

In answering such a question, it seems promising to investigate soccer players gaze behavior to learn about their observational strategies. An approach to investigate the cognitive processing of tactical skills in sports is the observation of humans gaze behavior. Therefore, the number of fixations in a perceived scene quantifies the gaze control and attention behavior in soccer games. The more fixations are executed on an object in a scene, the more object properties are perceived, and the better object functionality will be detected (Land & Tatler, 2009). Thus, the number of fixations can be an indicator for attention towards an object. Roca and colleagues (2011) found that soccer experienced players executed more fixations of shorter duration during the decision for an appropriate motor reaction of defense-oriented individual tactics in soccer. Williams, Davids, Burwitz, and Williams (1994) found in their study that experienced soccer players responded quicker to open play situations in soccer than inexperienced soccer players. Main difference in gaze behavior was that inexperienced players fixated more on the ball, and experienced soccer players more on peripheral aspects of the display. At least similar results were found by Williams and Davids (1998) for 1-on-1 soccer simulations, but not for 3-on-3 simulations. In this case the experienced players fixated longer on the hip region of the players in the simulation as compared to inexperienced players. Vaeyens, Lenoir, Williams, and Philippaerts (2007) investigated adolescent soccer players and their gaze behavior while passing a ball to one of the teammates. Their elite and sub-elite players were better than regional players were, but novice players showed a few parallels in their gaze behavior. The authors Vaeyens, Lenoir, Williams, Mazyn and Philippaerts (2007) demonstrated for offense plays that the evaluation of more complex scenarios (e.g., 5 vs 3 or 4 vs. 3 in comparison to 2 vs. 1 or 3 vs. 1) discriminated better between the different expertise levels of the participants. More experienced soccer players shifted their gaze between the player in possession of the ball and other areas as compared to less experienced soccer players. Thus, studies of gaze control in sport tactics revealed that experienced soccer players are usually faster, and their decisions are of higher quality than those of inexperienced soccer players. However, it remains unclear whether superior decision-making skills base on expert's early detection of relevant cues or on their ability to process the fixated information more effectively.

Overall, differences in gaze behavior may be due to different task constraints (Vickers, 2009). However, differences in the cognitive representation structures, for instance, of the instep kick in soccer

(Essig, Weigelt, Berger, Thieschäfer, & Schack, 2009) lead to different gaze patterns during a decision-making process. Experts, for instance, focused more on the relevant information of the task, which can be described as a more functional attention (Raab & Johnson, 2007). It seems that tactic-related structures in long-term memory evolve with an increasing level of expertise. Sport and cognitive science researchers recommend that research questions should be focused directly on structure formation in the long-term memory at a tactical level which influences the performance (Carling, Reilly, & Williams, 2009; Carling, Williams, & Reilly 2005; Hughes & Bartlett, 2002). The present study is designed to investigate the cognitive representation and the visual attention of team-specific tactics in soccer by the application of different match situations that afford a particular tactic. The significance of this study is evident in two perspectives. First, from a theoretical point of view, the cognitive representation and cognitive processing of team-specific tactics can be considered a crucial ability within the performance determining skills in soccer. Second, from an applied point of view, the knowledge about the individual cognitive representation of team-specific tactics in soccer has the potential to plan specially designed training sessions for athletes, and facilitates the individual learning processes. Therefore, this study investigates individual cognitive representations and the cognitive processing of team-specific tactics in soccer with regard to different levels of expertise. It was hypothesized that the cognitive representation of team-specific tactics of more experienced soccer players, in contrast to less experienced soccer players, will be aligned to the functional demands of the afforded tactic in soccer (Experiment 1). Additionally, this study examined the influence of soccer-specific expertise on the cognitive processing of team-specific tactics on a temporal level (Experiment 2). It was hypothesized that more experienced soccer players would determine an appropriate tactical behavior faster than less experienced soccer players. The remaining question is which group characteristics are responsible for possible reaction time advantages of more experienced soccer players. It can be speculated that this group used a different gaze behavior as compared to the less experienced soccer players. In relation to the results of Essig and colleagues (2009), the formulated hypothesis states that more experienced soccer players should execute more fixations of shorter durations than less experienced soccer players while deciding for the correct tactical behavior. Overall, it seems reasonable; if the cognitive representation structure is functionally organized, it should influence the cognitive processing of team-specific tactics in soccer.

Methods

Two experiments were conducted in order to investigate soccer players' cognitive representation, the cognitive processing, and the visual attention patterns of team-specific tactics in soccer. Both experimental setups used the identical stimulus material.

Stimulus Material

Within both experimental setups, four different team-specific tactics in soccer were investigated. These team-specific tactics were (1) counter-attack, (2) change sides, (3) back to defense, and (4) pressing. Thus, the match situations were designed in correspondence to the description of fundamental team-specific tactics (Lucchesi, 2008a, 2008b; Marzialli & Mora, 2009). Every stimulus depicted a match situation displayed on a coach’s board from a birds-eye perspective. All players on the pitch were depicted as equilateral triangles. The orientation of the board was kept constant, whereby the participant’s team moved offensively in an upward direction indicated by blue triangles, and the opponent’s team moved downward indicated by orange triangles. Figure 5.1 presents exemplarily the stimulus design. The letters “TW” (the German abbreviation for the word goalkeeper) highlighted the goalkeepers. A black vertex within each triangle indicated the viewing direction of each player. Additional information was provided in the stimulus material by usage of generally accepted signs and symbols (e.g., solid lines indicated passing directions and dashed lines running paths). This kind of stimulus presentation was employed to avoid conflicting cognitive processes involved in the perception of body postures (like the perceptual and motor resonance phenomena described by Schütz-Bosbach & Prinz (2007) with the goal to focus solely on the cognitive structure formation of tactics.

Before the study commenced, an evaluation study was conducted to assess the relevant match situations and define an appropriate stimulus material. The designed match situations (*N* = 28) were judged by experienced coaches (*N* = 8, holding at minimum an A-license from the Deutscher Fußball-Bund and the Union of European Football Associations). These coaches were asked to how much percent (between 0 and 100) the depicted match situation is typical for the afforded team-specific tactic. Coaches’ judgments were inhomogeneous according to the Fleiss Kappa statistic for all raters (κ = 0.263; Landis & Koch, 1977). Due to this inhomogeneity, an item fit (IF) was calculated. This item fit was calculated by the subtraction of the coefficient of variation multiplied with 100 from the mean. Via this item fit, the final stimulus set was defined (*n* = 12). Table 5.1 provides an overview of the Kappa statistics and item fit statistics.

Experiment 1

Experiment 1 used a method called *Structural Dimension Analysis of Mental Representations (SDA-M)*, which has been used to implicitly access cognitive representation of complex motor actions in the human long-term memory (Schack, 2012; Schack & Mechsner, 2006). These authors offer evidence of a functional organization of cognitive representations in the control of complex human movements. By this method, the strong relationship between the performance outcome of complex motor actions and the cognitive representation structure is revealed. The biomechanical demands of successful movement execution are reflected within the cognitive representation structure. However, not only complex human movements were investigated. Additionally, differences in the memory structure of children regarding the evaluation of comfortable and uncomfortable grasp postures have been revealed by this method (Stöckel, Hughes, & Schack, 2012).

Table 5.1

Overview of used Stimuli.

The stimuli are assigned to the team-specific tactics from participants' team perspective including a brief description of the scenario. The short description defines broadly the used match situation. The calculation of an item fit based on coaches' decisions for each stimulus formed the basis to choose three out of seven adequate stimuli for the team-specific tactics applied in the Experiments 1 and 2.

No	Playing direction	Team-specific tactic	Description of match situation	Mean	SD	Item fit
1	Offense	Counter-attack	Steal on the right side in the midfield	80.63	11.48	66.39
2	Offense	Counter-attack	Steal after an opposing corner kick	86.25	23.87	58.58
3	Offense	Counter-attack	Steal in the center of the midfield	75.63	29.45	36.68
4	Defense	Pressing	On the left side in the attack zone	88.38	08.85	78.36
5	Defense	Pressing	On the right side in the midfield zone	76.13	17.57	53.04
6	Defense	Pressing	On the right side in the attack zone	77.00	21.02	49.70
7	Offense	Change sides	Shift game play via the goalkeeper	91.88	12.52	78.25
8	Offense	Change sides	Shift game play to the left side in the midfield	90.00	10.69	78.12
9	Offense	Change sides	Shift game play to the right side in the midfield	89.00	11.25	76.36
10	Defense	Back to defense	After turnover on the left side in the midfield	83.13	23.14	55.29
11	Defense	Back to defense	After turnover in the center in the attack zone	75.00	18.52	50.31
12	Defense	Back to defense	After turnover on the right side in the midfield	78.13	25.35	45.68

Furthermore, the memory structure of general skills such as movement directions was found to have an important impact on motor performance (Lex, Weigelt, Knoblauch, & Schack, 2012). The applied stimuli in these studies (i.e., grasp postures or movement directions) can be compared to the cognitive equivalents of the basic concepts in object categorization described by Mervis and Rosch (1981). Experiment 1 used the match situations described before which afford a particular team-specific tactic.

Participants

Participants (*N* = 38) provided written consent prior to the experiment, and received no financial compensation for their participation. The study was conducted in accordance with the ethical principles stated within the declaration of Helsinki (1964), and met the criteria of the ethical guideline from the local university. Both groups of participants had soccer experience with the more experienced players performing on a higher competitive level than players of the other group do. The group of less experienced soccer players (*n* = 20) were on average 26.2 (*SD* = 4.2) years old. These players had on average a soccer-specific experience of 3.2 (*SD* = 4.2) years, acquired during (a) club soccer training up to 8th league, (b) university courses, or (c) during non-organized leisure time activities. The group of more experienced soccer players (*n* = 18) were on average 21.8 (*SD* = 2.7) years old. These players had on average a soccer specific experience of 17.3 (*SD* = 3.3) years, acquired during specific soccer training. The more experienced players were members of an U23-team competing in a professional German second league club. The U23-team played in the fourth German league while this study was conducted.

Task & Procedure

Three match situations for each team-specific tactic were used to measure the cognitive representation of team-specific tactics in soccer with the SDA-M. Each level of expertise was tested within a single session. Before the experiment commenced, all participants were informed about each stimulus in the tactic board design, given an explanation of the symbols, and the teams' playing directions. They were not informed about the intended team-specific tactics. The match situations were displayed on a white wall (projection size 2 x 2.5 m) to ensure perfect sight for every participant. The projection was split into two equally sized parts (see Figure 5.1). At the center of the left part of the screen, one randomly chosen stimulus was presented in an anchoring position. The stimulus in the anchoring position was compared with every other randomly chosen stimulus appearing at the center of the right part of the screen. For every stimulus pair (i.e., presented stimulus on the left and on the right part of the screen), participants indicated whether or not their team had to react with the identical team-specific tactic. Participants did not explicitly label or name the underlying team-specific tactics. This is an obvious difference between the current task and a simple sorting or rating task. The split procedure was designed to probe participant's implicit knowledge about tactics. Participants needed to understand implicitly the underlying tactic and did not need to provide explicit terms and specifications for that tactic. The decisions were made without time limit, entered into a form, and later transferred by the experimenter into the software.

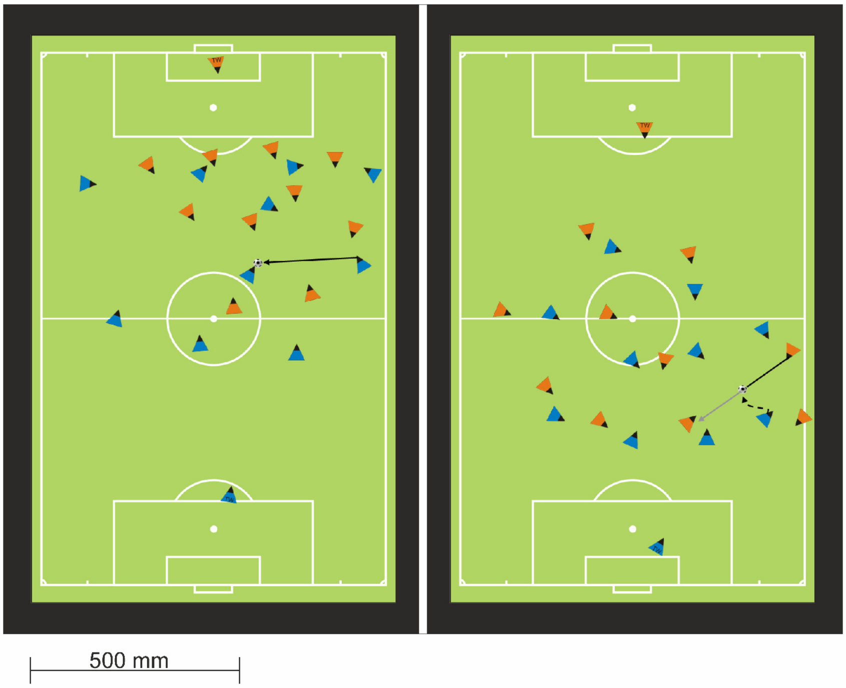

Figure 5.1 Setup for the Cognitive Measurement of Tactics in Soccer. The colored stimuli were projected on a white wall by a beamer. The stimulus on the left side was in anchoring position and compared to every other stimulus. After this procedure, the anchoring position was taken by the next randomly chosen stimulus, and again compared with every other stimulus.

Data analysis

The acquisition of participants' decisions on the comparison of the twelve different match situations with each other consisted of three steps. First, the split procedure allows for a distance scaling between the different match situations. This reveals proximity data between the different match situations. The proximity data between match situations was transformed by *z*-normalization and converted into a

Euclidean distance matrix. This matrix contained the Euclidean distances between each pair of match situations. The Euclidean distances were the basis for a hierarchical cluster analysis aimed at grouping the match situations. In the second step, the cognitive representation of team-specific tactics in soccer was calculated using an unweighted average-linkage hierarchical cluster analysis. This analysis is based on the Euclidean distances between the match situations. The numbers at the conjunctions within each resulting dendrogram reports the Euclidean distances between a given pair of match situations. Each dendrogram reflects the cognitive representation of team-specific tactics in soccer within a specific group of participants. A critical Euclidean distance is statistically estimated as the value d_{crit} = 4.552 for a significant alpha-level of p = .01. All connected match situations below the critical value form distinct clusters. Conversely, all match situations above the critical value are treated as non-distinct clusters. In the third step, these generated cognitive representations of team-specific tactics in soccer were tested for structural homogeneity using a between-groups invariance measure. The invariance measure compared resulting dendrograms between groups based on the common number of shared clusters, the common number of match situations within each cluster, and the average quantities of evolved clusters. In the present experiment, the statistical threshold for accepting invariance between representation structures is set to λ = .68 as an empirically estimated value. Schack (2012) provides further details of the described procedure.

Experiment 2

Participants

Participants (*N* = 20) provided written consent prior to the experiment, and received no financial compensation for their participation. The study was conducted in accordance with the ethical principles stated within the declaration of Helsinki (1964), and met the criteria of the ethical guideline from the local university. Both groups of participants had soccer experience with the more experienced players performing on a higher competitive level than the players of the other group do. The group of less experienced soccer players (*n* = 10) were on average 22.7 (*SD* = 2.0) years old. These players had on average a soccer-specific experience of 0.4 (*SD* = 1.0) years, acquired during (a) club soccer training up to 7th league, (b) university courses, or (c) during non-organized leisure time activities. The group of more experienced soccer players (*n* = 10) were on average 25.0 (*SD* = 3.8) years old. These players had on average a soccer specific experience of 19.8 (*SD* = 4.4) years, acquired during specific soccer training. The more experienced players received the soccer experience as adults in the first and up to the fourth league in Germany.

Task & Procedure

Experiment 2 measured participants' decisions on team-specific tactics within a two-choice reaction time task. The used match situations were explained to participants in terms of the symbols and abbreviations prior to the experiment. Subsequently, participants were informed about the four team-specific tactics used in this study. The experimental procedures were conducted to deliver additional insights about the cognitive processing of team-specific tactics in soccer.

The task was for the participants to make a decision between two pre-defined team-specific tactics in the context of one match situation as accurately and as quickly as possible (see drawing in Figure 5.2a). Each reaction button was constrained to one team-specific tactic, and the participants were provided with verbal instructions before every practice and test block. The task was to decide whether the presented stimulus belonged to one team-specific tactic or the other. To ensure that participants understood the team-specific tactics, and to make them familiar with the configuration of buttons, a short practice block (i.e., six trials) was conducted before every test block. Overall, Experiment 2 was conducted in six blocks (i.e., including one practice and one test block each) to cover all potential button configurations: pressing vs. back to defense, counter-attack vs. change sides, pressing vs. counter-attack, pressing vs. change sides, back to defense vs. counter-attack, and back to defense vs. change sides. The order of the presented stimuli was randomized across trials, and the locations of the respective reaction buttons were balanced across participants. The experiment was designed with the VDesigner, a visual programming environment for eye-tracking experiments (Koesling & Ritter, 2001).

At the beginning of each block, the word “Achtung” (German for “attention”) was displayed for 1500 ms to draw participants’ attention towards the monitor and inform them that the test would start immediately. Stimuli were presented within the procedure depicted in Figure 5.2b. First, a fixation cross was shown at the center of the screen for 250 ms before each stimulus. Second, the presented stimulus remained on the screen until participants pressed one of the two reaction buttons. Immediately after a correct decision, a blank screen was shown for 500 ms and the next fixation-cross appeared. If the decision was incorrect, an error message (i.e., "Fehler"; German for "error") was displayed for 500 ms before the next fixation cross. The error message provided feedback about participants' accuracy to remind them of the task.

While participants made their decisions on the presented stimuli (i.e., between stimulus onset and button press) their eye movements were recorded using the SR Research Eye-Tracker. This system employs a headset with two cameras to enable binocular eye-movement recording. Further features of the EyeLink II system are a high sampling rate up to 500 Hz and an average on-screen gaze position error between 0.5° and 1.0°. The whole system was calibrated for drift correction every five trials within each block, to minimize the measurement error as much as possible, and to keep the experiment as comfortable as possible for the participants.

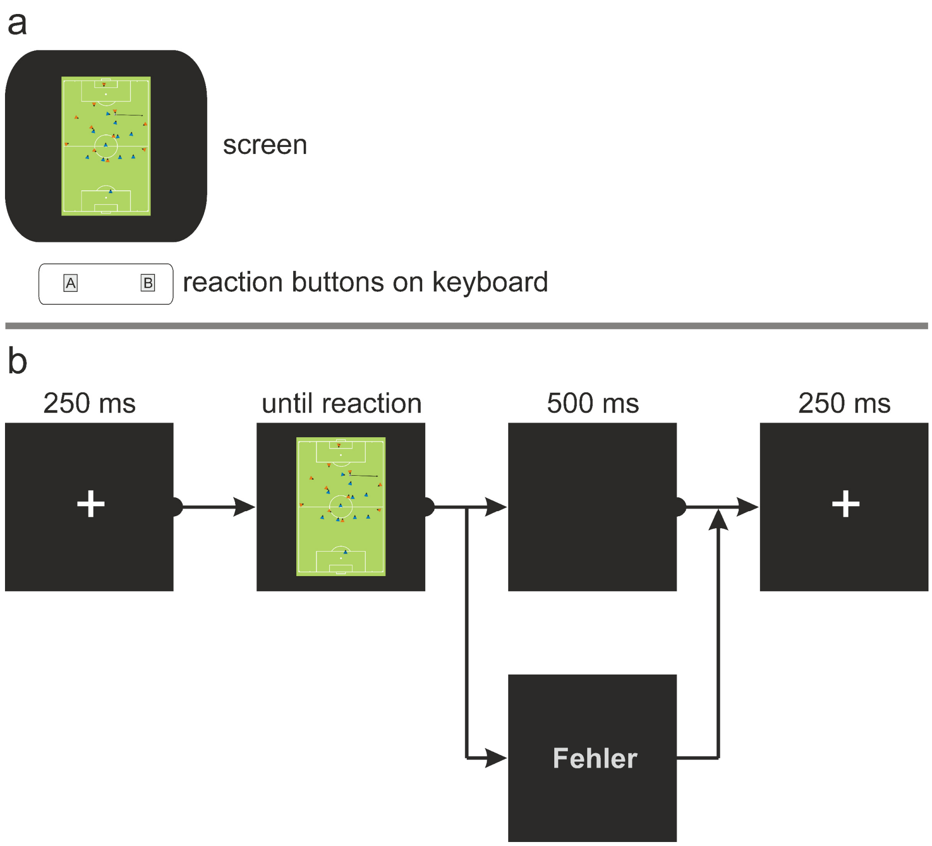

Figure 5.2 A schematic drawing of the used setup. One stimulus was presented on the screen. Participants logged their decisions by usage of two reaction buttons (each indicating a certain tactical behavior) on a keyboard, which was centered in front of the screen. The respective button configurations were introduced and tested by each participants before the test sessions. (b) Trial sequence of the reaction time task.

Data analysis

The number of errors and the corresponding reaction times were recorded and analyzed. From eye-tracking data the parameters number of fixations and fixation duration were extracted. The spatial resolution of eye movements was analyzed by the evaluation of the number of observed pixels within each trial extracted from corresponding attention maps. An attention map shows the activation of each pixel in the observed stimulus with regard to the total time an observer spent on these locations. Attention maps are used to highlight areas within a stimulus receiving high attention by the observer. On the opposite areas that were observed sparsely are blurred (Essig, Pomplun, & Ritter, 2006). The attention map pixel values are ranging between 0.0 (i.e., no attention) to 1.0 (i.e., high attention).

A two-way (tactic x group) ANOVA were used to evaluate the results of both experiments in terms of reaction times, number of fixations, fixation duration, and observed pixels. The within factor *tactic* consisted of four levels (i.e., counter-attack, change sides, pressing, and back to defense), and the between factor *group* consisted of two levels (i.e., more experienced and less experienced soccer players). If Mauchly’s test revealed that the sphericity assumption was violated in the ANOVA, the degrees of freedom were corrected by estimation of sphericity according to the Greenhouse–Geisser correction.

Results

Experiment 1

Figure 5.3a illustrates the mean cognitive representation structure of the group of less experienced soccer players. Their representation shows two distinct clusters. Cluster 1 (combining the match situations 12, 10, 6, 5, 11, 4) integrates all match situations aligned to defensive tactics, in which the opposing team is in possession of the ball. Cluster 2 (combining the match situations 3, 1, 9, 7, 8, 2) integrates all match situations aligned to offensive tactics, in which the target team is in possession of the ball. There is no further functional clustering in the cognitive representation of team-specific tactics in less experienced soccer players.

Figure 5.3b illustrates the mean cognitive representation structure of the group of the more experienced soccer players. Their representation shows a separation of the match situations in four distinct clusters. Cluster 1 (combining the match situations 9, 8, 7) integrates all match situation related to the team-specific tactic ‘change sides’, and Cluster 2 (combining the match situations 2, 3, 1) all situations of ‘counter-attack’. Above the critical Euclidean distance (d_{crit} = 4.552) these two clusters are merged into the offensive tactics. Cluster 3 (combining the match situations 6, 5, 4) integrates the match situations related to team-specific tactic of ‘pressing’, and Cluster 4 (combining the match situations 11, 12, 10) integrates all match situations related to ‘back to defense’ tactics. The clusters ‘pressing’ and ‘back to defense’ are connected with each other above the critical Euclidean distance (d_{crit} = 4.552), pointing at the existence of a representation level integrating all defense strategies.

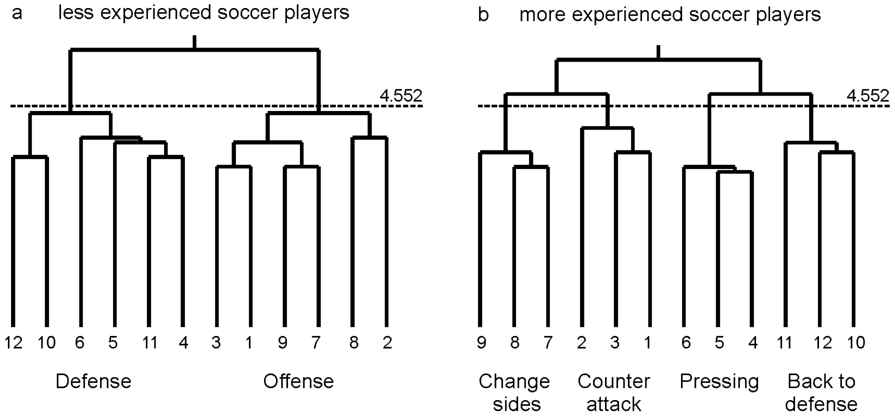

Figure 5.3 Cognitive representation of team-specific tactics in soccer for soccer novices (a) and soccer experts (b). The number at the bottom represents the different match situations. The height at each conjunction represents the Euclidian distance between match situations. The lower the conjunction, the closer the connection between the match situations. The dashed line represents the critical Euclidian distance where the branches were cut off. The cognitive representation structures show that experts, in contrast to novices, possess a functional representation of team-specific tactics in soccer.

The invariance measure examining for homogeneity between evolved representation structures revealed invariance ($\lambda_{more\_exp} = 1.0$) of the cognitive representation of team-specific tactics for more experienced soccer players in comparison to an ideal structure. Thus, more experienced soccer players' cognitive representation can be interpreted as identical to an ideal structure. The cognitive representation of team-specific tactics in soccer for less experienced soccer players revealed no invariance ($\lambda_{less\_exp} = 0.42$) in comparison to an ideal structure. Both structures share less common features, and thus, they cannot be interpreted as similar to each other.

Experiment 2

Overall, in 15.3 % of all trials, the participants decided incorrectly or data was classified as outlier when decisions were longer than two standard deviations from the mean. ANOVA results for the measured reaction times of the participants correct answers revealed a significant main effect for the factor *group*, $F(1,18) = 5.486$, $p < .05$, $\eta^2 = .234$. The experienced soccer players ($M = 1488.2$ ms, $SD = 562.2$) decided faster in comparison to the less experienced soccer players ($M = 2258.9$ ms, $SD = 1121.0$). In addition, a significant main effect was observed for the factor *tactic*, $F(3,54) = 7.694$, $p < .01$, $\eta^2 = .299$. The participants decided faster for the tactic ‵counter attack' ($M = 1533.2$ ms, $SD = 733.2$), as for ‵change sides' ($M = 1558.7$ ms, $SD = 910.4$), as for ‵pressing' ($M = 2181.8$ ms, $SD = 1059.7$), and as for the tactic ‵back to defense' ($M = 2220.5$ ms, $SD = 1120.9$). No significant interaction between the factors was observed.

ANOVA results for the average fixation duration of the participants correct answers revealed no significant main effect for the factor *group*, $F(1,18) = 0.019$, $p = .89$, $\eta^2 = .001$. As well the experienced soccer players ($M = 378.9$, $SD = 75.0$) as the less experienced soccer players ($M = 383.4$, $SD = 104.7$) had a similar average fixation duration. But, a significant main effect was observed for the factor *tactic*, $F(3,54) = 4.170$, $p < .05$, $\eta^2 = .188$. The participants had a smaller average fixation duration for the tactic ‵pressing' ($M = 335.8$ ms, $SD = 48.5$), as for ‵back to defense' ($M = 382.5$ ms, $SD = 81.1$), as for ‵counter attack' ($M = 400.4$ ms, $SD = 104.7$), and as for the tactic ‵change sides' ($M = 406.0$ ms, $SD = 122.2$). No significant interaction between the factors was observed.

ANOVA results for the measured number of fixations of the participants correct answers revealed a significant main effect for the factor *group*, *F*(1,18) = 5.031, $p < .05$, $\eta^2 = .218$. The experienced soccer players (*M* = 4.4, *SD* = 2.0) needed less fixations in comparison to the less experienced soccer players (*M* = 6.8, *SD* = 3.6). In addition, a significant main effect was observed for the factor *tactic*, *F*(3,54) = 4.543, $p < .05$, $\eta^2 = .202$. The participants needed less fixations for the tactic 'counter attack' (*M* = 4.7 ms, *SD* = 2.1), as for 'change sides' (*M* = 4.9 ms, *SD* = 3.1), as for 'back to defense' (*M* = 6.3 ms, *SD* = 3.8), and as for the tactic 'pressing' (*M* = 6.6 ms, *SD* = 3.4). No significant interaction between the factors was observed. The results are summarized as bar plots in Figure 5.4.

Moreover, the areas observed by the participants have been analyzed for each match situation. The corresponding attention maps of the correct answers delivered insights regarding the amount and the frequency of observed pixels between stimulus onset and participants reaction. ANOVA results for the number of observed pixel within each match situation revealed a significant main effect for the factor *group*, *F*(1,18) = 17.837, $p < .01$, $\eta^2 = .498$. The experienced soccer players (*M* = 25944.8 px, *SD* = 6057.0) observed less pixels within each match situation than the less experienced soccer players (*M* = 37123.6 px, *SD* = 9603.7). Additionally, a significant main effect was observed for the factor *tactic*, *F*(3,54) = 6.568, $p < .01$, $\eta^2 = .267$. The participants observed less pixels in the match situations of the tactic 'back to defense' (*M* = 27954.8 px, *SD* = 10088.2), as for 'counter attack' (*M* = 29167.6 px, *SD* = 8477.3), as for 'change sides' (*M* = 34490.3 px, *SD* = 10798.3), and as for the tactic 'pressing' (*M* = 34524.1 px, *SD* = 9093.4). No significant interaction between the factors was observed.

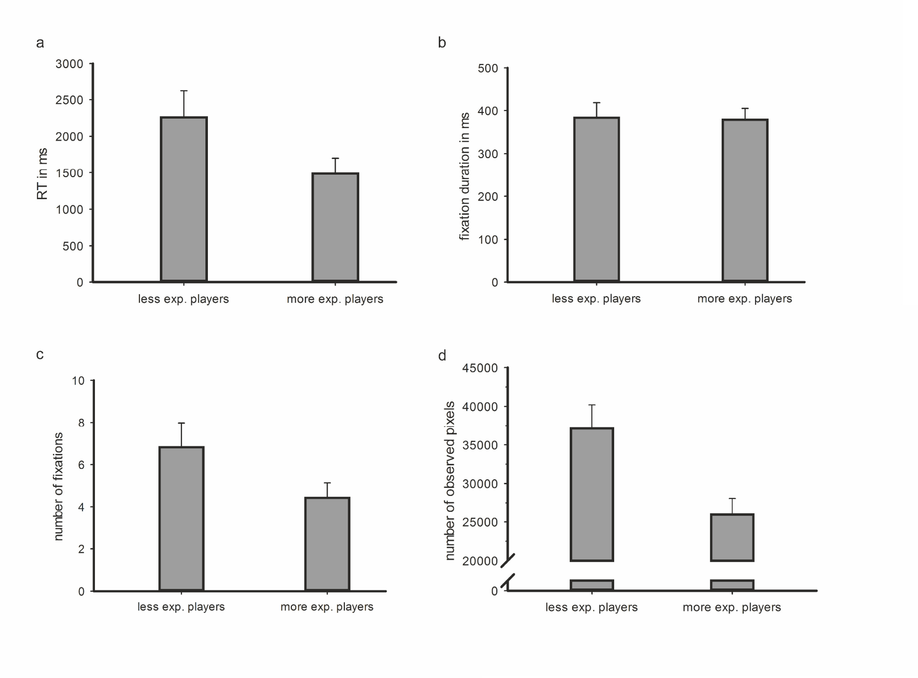

Figure 5.4 The bar plots show mean results and the error bars (95% confidence interval) of the less and more experienced soccer players. Figure 4a shows the reaction times, where the more experienced soccer players needed significantly less time to make a correct judgment of the match situation with regard to the appropriate team-specific tactic. Figure 4b displays the mean fixation duration of the correct decisions. There is no difference between less and more experienced soccer players. Figure 4c shows the mean number of fixations made between stimulus onset and reaction. The more experienced soccer players needed significantly less fixations as compared to the less experienced soccer players. Figure 4d indicates the mean number of pixels observed during the decision-making process. The more experienced soccer players observed significantly less pixels within the stimulus material as compared to the less experienced soccer players.

In addition, attention maps visualize the observation strategies. Figure 5.5 shows the attention maps of one match situation for each team-specific tactic of both groups. Areas highlighted in red indicate areas, which received high attention. Areas highlighted in yellow, green, and blue indicated areas sparsely observed. Blurred areas where not observed at all during the decision-making. The attention maps visualize the amount of observed pixels for selected match situations.

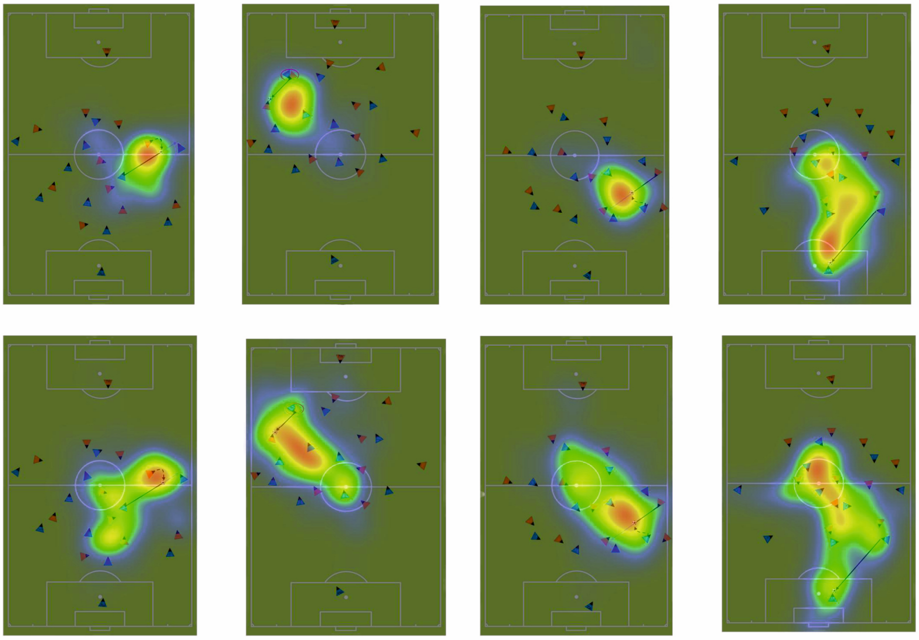

Figure 5.5 The attention maps for one match situation of each team-specific tactic for the more (upper row) and the less (lower row) experienced soccer players. The match situations represent from left to right: back to defense, pressing, counter-attack, and change sides match situations. Areas highly observed are indicated by red color, whereas areas of less attention are indicated in decreasing order by yellow, green, light green, and blue color. The blurred areas are not attended. Experts' attention is not as distributed as novices are. It seems that they are more focused on certain areas of the stimuli.

Discussion

This study was designed to examine the cognitive representation of team-specific tactics in soccer. The comparative performance of two different groups was examined – a group of more experienced soccer players and a group of less experienced soccer players. The storage and the cognitive processing of information regarding team-specific tactics in soccer were measured in participants' memory in an experiment via the cognitive representation structure and a reaction time task. Data supports the hypothesis that more experienced soccer players' memory structure of team-specific tactics is hierarchically organized as compared to less experienced soccer players. Less experienced soccer players' cognitive representation of team-specific tactics in soccer showed a clear separation of tactics related to the playing direction (i.e., offense or defense). No additional parameters constitute the cognitive representation structure of team-specific tactics of less skilled soccer players. In contrast, the more experienced soccer players showed a functional organization of team-specific tactics in soccer that are aligned with the four soccer-specific tactical concepts (counter-attack, pressing, change sides, and back to defense) investigated in this study. Additionally, these four tactical concepts form separate clusters in the long-term memory of more experienced soccer players. It can be assumed that these team-specific tactics are represented as independent units within the memory structure. Moreover, the two defense and two offense team-specific tactics are connected at a higher level in more experienced soccer players. According to these findings, it can be proposed that this approach is able to indicate relevant cognitive representations of team-specific tactics in soccer. This extends sport science research by not only documenting specific performance statistics (as an example see

Lago-Ballesteros & Lago-Peñas, 2010), but also by moving beyond such documentation (Vilar, Araújo, Davids, & Button, 2012). The present research offers insights into the cognitive representation of team-specific tactics in soccer usually difficult to explicitly address by the players themselves. Moreover, this parameter is difficult to observe during a soccer match because the observer cannot definitively know whether an observable behavior base on improved perception, on enhanced physical skills, or on cognitive representation structures. Therefore, all performance-influencing factors need to be extracted and analyzed to draw an extensive picture of the soccer performance of athletes. The cognitive representation of team-specific tactics possess the potential to characterize soccer performance of athletes, which can lead to individual success. Hughes and Bartlett (2002) stated that, performance indicators like the cognitive representation should form an individual profile that constitutes ideal athletic performance in comparison to recent performance.

Experiment 2 used participants comparable to Experiment 1 (i.e., in terms of age and soccer experience), and was designed to examine the cognitive and perceptual processing of team-specific tactics in soccer. Differences in behavioral response and observation strategies were observed between less and more experienced soccer players. Experiment 2 provides evidence that more experienced soccer players needed less time as compared to less experienced soccer players to judge match situations in correspondence to a certain team-specific tactic. The observation strategies during the decision-making process of both groups delivered evidence that mainly the number of fixations necessary to evaluate a match situation is an influencing variable on the reaction time. The mean fixation duration were the same for both groups. Thus, the less experienced soccer players needed more fixations at more locations for each match situation, which led to longer reaction times. The hypothesis that more experienced soccer players determine an appropriate tactical behavior faster than less experienced soccer players can be assumed. The data from Experiment 2 provide evidence that more experienced soccer players are able to classify domain-specific patterns of play faster than less experienced soccer players are. Previous expertise studies have also offered evidence for an advanced classification of domain-specific patterns of play (i.e., in terms of recalling more patterns) by experts (Abernethy, Baker, & Côté, 2005). Importantly, this has been shown in domains like chess (Kiesel, Kunde, Pohl, Berner, & Hoffmann, 2009; Simon & Chase, 1973), as well as within the sports domain (Helsen & Starkes, 1999; Ward & Williams, 2003; Williams, Davids, Burwitz & Williams, 1993). A likely explanation for this effect is that, more experienced players may possess a larger database of chunks, which allows them the faster cognitive processing of such match situations (Williams, Hodges, North, & Barton, 2006). So, the present study adds to the knowledge about parameters in decision-making of team-specific tactics in soccer.

Experiment 2 delivered evidence that the observation strategies were different between the two expertise levels. However, the hypothesis that more experienced soccer players make more fixations of shorter duration must be rejected. The more experienced players needed less fixations of same fixation duration while observing less pixels in the match situations as compared to less experienced soccer players.

This finding contradicts the finding of Roca and colleagues (2011). Potential reason for this discrepancy could be the application of a different stimulus material. Roca and colleagues (2011) used video sequences and the present study used static images of coach board designs to indicate the corresponding match situations. The video material contained information about the tactical behavior, but also information about the motor behavior of the involved players. If participants observe the motor behavior, which corresponds to their field of expertise (i.e., soccer), they activate corresponding cognitive representations. Thus, the brain activity of participants observing an experienced motor action reveals the influence of motor expertise on action observation (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Schütz-Bosbach & Prinz, 2007). Additionally, Williams and Davids (1998) already found that more experienced soccer players pay more attention to body postures than less experienced soccer players do. Therefore, the present study used static pictures to focus on the tactical information. In addition, the eye-tracking data of the present study emphasizes the findings of Williams, Davids, Burwitz, and Williams (1994) that experienced soccer players show a different pattern of attention distribution (i.e., the more experienced soccer players fixated peripheral targets) during their decision-making as compared to less experienced soccer players. Vaeyens, Lenoir, Williams, and Philippaerts (2007) showed that successful decision-makers in soccer spent more time in fixating the player in possession of the ball and shifted their gaze more frequently between that player and other areas of the stimulus. This finding is contradictory to Roca and colleagues (2011) and the results of the present study. The reason can be that Vaeyens, Lenoir, Williams, and Philippaerts (2007) used only group specific tactics involving not more than eight players. In addition, the viewing angle was from a central midfielder in only offense plays. It can be assumed that the restrictions triggered a special gaze behavior, especially when the participants had to imagine themselves as the midfielder indicated in the video sequences. The data of Vaeyens, Lenoir, Williams, Mazyn and colleagues (2007) delivered evidence that with an increasing complexity of the stimulus material (i.e., in their study involvement of players from 3 up to 8) the number of fixations increased. The present study used the highest level of complexity, because all players were involved. That is the reason for the higher amount of fixations found in the participants of the present study. The drawback of the studies of Vaeyens, Lenoir, Williams, and Philippaerts (2007) and Vaeyens, Lenoir, Williams, Mazyn and colleagues (2007) is that, both were conducted with only adolescent players. With regard to the curricula of the soccer teaching programs, it is obvious that adolescents cannot be developed as adults in terms of tactics.

It can be assumed that the gaze behavior is controlled based on cognitive representations of team-specific tactics in soccer in a comparable manner to the gaze behavior in the perception of complex motor actions (Flanagan & Johansson, 2003). The present results suggest that the cognitive representation of team-specific tactics in soccer are responsible for the gaze behavior in the perception of such tactics in a comparable manner as for cognitive representations of complex motor actions. It can be assumed that more experienced soccer players needed less fixations to evaluate the underlying tactics because they possess a functional knowledge of the team-specific tactics. Thus, they were able to react faster, because they identified the most informative locations for their decisions.

The main effect for tactic in Experiment 2 can be explained by the different structure of the used match situations. However, interestingly the reaction times were fastest for the offense tactics where participants needed as well less fixations to judge them in comparison to the defense tactics. Moreover, the fixation duration was shorter for the defense tactics as compared to the offense tactics. These effects lead to the assumption that offense tactics were processed differently than defense tactics. The reason therefore might be that, offense tactics afford an action and defense tactics afford a reaction. The appropriate defense reaction on the possibilities in opponents’ offensive team-specific tactics afforded more fixations of shorter duration to evaluate all possibilities of the opponent. That means, in defense play the attention is directed between opponents and own team members. Whereas, the production of a successful offense play affords less fixations of longer duration, because the attention might be focused towards the own players.

The attention maps visualize the spatial distribution of attention across the different match situations. It is observable that more experienced soccer players attention seems to be more focused on selected spots within each match situation, because the inspected areas are smaller as compared to less experienced soccer players. Taken more experienced soccer players number of fixations and the fixation duration into account it seems that they exactly know where relevant cues are in the match situations for a proper decision-making. More experienced soccer players seem to be able to detect relevant cues of match situations and analyze their impact on the decision-making process. That enables more experienced soccer players to decide faster. These findings add to the existing knowledge that experienced soccer players are better able to evaluate and prioritize a possible individual tactical behavior (e.g., passing options) than novices (Ward & Williams, 2003).

From an applied perspective, practical training implications can be derived from the results of the present study. It can be reasoned that more experienced soccer players possess a functional cognitive representation of team-specific tactics in soccer, and their cognitive processing of such tactics differs from less experienced soccer players. Specifically, if an athlete’s memory structure has an influence on the time it takes to decide for an appropriate tactic, then coaches should address players’ cognitive representation explicitly within training sessions. That is what coaches are already attempting, albeit without verified knowledge about their athletes’ memory structures. Thus, the measurement of cognitive representations of team-specific tactics in soccer has the potential to meet the criteria of a diagnostic tool, which is able to predict future sporting behavior (see Jones, Mellalieu, & James, 2004; O'Donoghue, 2005). Importantly, the measurement of cognitive representations has already been successfully implemented into a training scenario in Judo (e.g., a Judo throwing technique called Uchi-Mata). Therefore, high-level experts possess inter-individual differences, which are addressed in practical training implications (Weigelt, Ahlmeyer, Lex, & Schack, 2011). It seems possible, then, to convey specific, individually adjusted training instructions from the cognitive representation in long-term memory.

Moreover, the proposed methods in the present paper investigated soccer players’ cognitive representations and the cognitive processing of team-specific tactics in soccer. The results of the studies facilitate the understanding of soccer experts’ tactical decision-making as proposed similarly by Vestberg, Gustafson, Maurex, Ingvar, and Petrovic (2012). In addition, the knowledge about the most informative locations during the decision-making process may also facilitate the learning. There are hints that the superior decision-making skill of experts may be related to an early cue perception and not to an advanced processing of fixated information. Thus, the evaluation of cognitive representations of team-specific tactics in soccer in combination with the measurement of gaze behavior has the potential to form the basis for the diagnostics in and the development of functional tactics training. Especially, the visual perception can be assessed easily during soccer games (i.e., by the usage of new eye-tracker hardware) to evolve visual and mental guided training techniques.

References

Abernethy, B., Baker, J., & Cote, J. (2005). Transfer of pattern recall skills may contribute to the development of sport expertise. *Applied Cognitive Psychology, 19*(6), 705-718. doi:10.1002/Acp.1102

Ali, A. (2011). Measuring soccer skill performance: a review. *Scandinavian Journal of Medicine and Science in Sports, 21*(2), 170-183. doi:10.1111/j.1600-0838.2010.01256.x

Calvo-Merino, B., Grezes, J., Glaser, D. E., Passingham, R. E., & Haggard, P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. *Current Biology, 16*(22), 1905-1910. doi:10.1016/j.cub.2006.07.065

Carling, C., Reilly, T., & Williams, A. M. (2009). *Performance Assessment for Field Sports*. Abingdon: Routledge.

Carling, C., Williams, A. M., & Reilly, T. (2005). *Handbook of Soccer Match Analysis*. Abingdon: Routledge.

Elferink-Gemser, M. T., Visscher, C., Richart, H., & Lemmink, K. A. P. M. (2004). Development of the tactical skill inventory for sports. *Perceptual and Motor Skills, 99*(3), 883-895. doi:10.2466/pms.99.3.883-895

Essig, K., Pomplun, M., & Ritter, H. (2006). A neural network for 3D gaze recording with binocular eye trackers. *International Journal of Parallel, Emergent and Distributed Systems, 21*(2), 79-95. doi:10.1080/17445760500354440

Essig, K., Weigelt, M., Berger, A., Thieschäfer, L., & Schack, T. (2009). Phenomena of perception-action-coupling in teamsports - An analysis of attention control on the basis of eye movements in soccer. Proc. 15th European Conference on Eye Movements, Southampton, England, 76.

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. *Nature, 424*(6950), 769-771. doi:10.1038/nature01861.

Garganta, J. (2009). Trends of tactical performance analysis in team sports: bridging the gap between research, training and competition. *Revista Portuguesa de Ciências do Desporto, 9*(1), 81-89.

Gonzaga, A. D. S., Albuquerque, M. R., Malloy-Diniz, L. F., Greco, P. J., & Teoldo da Costa, I. (2014). Affective decision-making and tactical behavior of under-15 soccer players. *PLOS ONE, 9*(6), e101231. doi:10.1371/journal.pone.0101231

Gréhaigne, J.-F., & Godbout, P. (1995). Tactical knowledge in team sports from a constructivist and cognitivist perspective. *Quest, 47*(4), 490-505. doi:10.1080/00336297.1995.10484171

Helsen, W. F., & Starkes, J. L. (1999). A multidimensional approach to skilled perception and performance in sport. *Applied Cognitive Psychology, 13*(1), 1-27. doi:10.1002/(SICI)1099-0720(199902)13:1<1::AID-ACP540>3.0.CO;2-T

Hodges, N. J., Huys, R., & Starkes, J. L. (2007). Methodological Review and Evaluation of Research in Expert Performance in Sport. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of Sport Psychology*. Hoboken (NJ): John Wiley & Sons.

Hughes, M. D., & Bartlett, R. M. (2002). The use of performance indicators in performance analysis. *Journal of Sports Sciences, 20*(10), 739-754. doi:10.1080/026404102320675602

Jones, N. M. P., Mellalieu, S. D., & James, N. (2004). Team Performance indicators as a Function of Winning and Losing in Rugby Union. *International Journal of Performance Analysis in Sports, 4*(1), 61-71

Kiesel, A., Kunde, W., Pohl, C., Berner, M. P., & Hoffmann, J. (2009). Playing chess unconsciously. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(1), 292-298. doi:2008-18581-020 [pii] 10.1037/a0014499

Knapp, B. (1977). *Skill in Sport: The Attainment of Proficiency*. London: Routledge.

Koesling, H., & Ritter, H. (2001). *VDesigner - A visual programming environment for eye tracking experiments.* Paper presented at the 11th European Conference on Eye Movements, Turku, Finland.

Lago-Ballesteros, J., & Lago-Peñas, C. (2010). Performance in Team Sports: Identifying the Keys to Success in Soccer. *Journal of Human Kinetics, 25*(1), 85-91. doi:10.2478/v10078-010-0035-0

Land, M. F., & Tatler, B. W. (2009). *Looking and acting : vision and eye movements in natural behaviour*. Oxford ; New York: Oxford University Press.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*(1), 159-174

Lex, H., Weigelt, M., Knoblauch, A., & Schack, T. (2012). Functional relationship between cognitive representations of movement directions and visuomotor adaptation performance. *Experimental Brain Research, 223*(4) doi:10.1007/s00221-012-3273-7

Lucchesi, M. (2008a). *Pressing* (S. Neuhaus, Trans.). Leer: ONLI Verlag.

Lucchesi, M. (2008b). *Wie gegen welche Taktik [How against which tactic]* (S. Neuhaus, Trans.). Leer: ONLI Verlag.

Marzialli, F., & Mora, V. (2009). *Moderne Fussballtaktik [Modern Tactics in Soccer]* (H. Goschala, Trans.). Leer: ONLI Verlag.

McGregor, S. J., Nicholas, C. W., Lakomy, H. K., & Williams, C. (1999). The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. *Journal of Sports Sciences, 17*(11), 895-903. doi:10.1080/026404199365452

McPherson, S. L., & Kernodle, M. W. (2003). Tactics, the neglected attribute of expertise. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert Performance in Sports - Advances on Research in Sport Expertise*. Champaign (Il): Human Kinetics.

McPherson, S. L., & Vickers, J. A. (2004). Cognitive control in motor expertise. *International Journal of Sport and Exercise Psychology, 2*(3), 274-300. doi:10.1080/1612197X.2004.9671746

Memmert, D. (2004). *Kognitionen im Sportspiel [Cognitions at Sport Games]*. Köln: Sport & Buch Strauß.

Memmert, D. (2006). *Optimales Taktiktraining im Leistungsfußball [Optimal Tactics Training in Soccer]*. Balingen: Spitta Verlag.

Mervis, C. B., & Rosch, E. (1981). Categorization of Natural Objects. *Annual Review of Psychology, 32*, 89-115. doi:10.1146/annurev.ps.32.020181.000513

O'Donoghue, P. (2005). Normative Profiles of Sports Performance. *International Journal of Performance Analysis in Sport, 5*(1), 104-119

Raab, M., & Johnson, J. G. (2007). Expertise-based differences in search and option-generation strategies. *Journal of Experimental Psychology: Applied, 13*(3), 158-170. doi:0.1037/1076-898X.13.3.158

Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M. (2011). Identifying the processes underpinning anticipation and decision-making in a dynamic time-constrained task. *Cognitive Processing, 12*(3), 301-310. doi:10.1007/s10339-011-0392-1

Schack, T. (2012). Measuring Mental Representations. In G. Tenenbaum, R. Eklund & A. Kamata (Eds.), *Handbook of Measurement in Sport and Exercise Psychology* (Vol. 1). Champaign, Illinois: Human Kinetics.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. *Neuroscience Letters, 391*(3), 77-81. doi:10.1016/j.neulet.2005.10.009

Schütz-Bosbach, S., & Prinz, W. (2007). Perceptual resonance: action-induced modulation of perception. *Trends in Cognitive Science, 11*(8), 349-355. doi:S1364-6613(07)00152-0 [pii]10.1016/j.tics.2007.06.005

Simon, H. A., & Chase, W. G. (1973). Skill in Chess. *American Scientist, 61*(4), 394-403. doi:10.1007/978-1-4757-1968-0_18

Stöckel, T., Hughes, C.M.L., & Schack, T. (2012). Representation of grasp postures and anticipatory motor planning in children. *Psychological Research*, 76(6), 768-776. doi: 10.1007/s00426-011-0387-7

Vaeyens, R., Lenoir, M., Williams, A. M., Mazyn, L., & Philippaerts, R. M. (2007). The effects of task constraints on visual search behavior and decision-making skill in youth soccer players. *Journal of Sport & Exercise Psychology, 29*(2), 147-169Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., & Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PLOS ONE, 7*(4), e34731. doi:10.1371/journal.pone.0034731

Vaeyens, R., Lenoir, M., Williams, A. M., & Philippaerts, R. M. (2007). Mechanisms underpinning successful decision making in skilled youth soccer players: an analysis of visual search behaviors. *Journal of Motor Behavior, 39*(5), 395-408. doi:10.3200/JMBR.39.5.395-408

Vickers, J. N. (2009). Advances in coupling perception and action: the quiet eye as a bidirectional link between gaze, attention, and action. *Progress in Brain Research, 174*, 279-288

Vilar, L., Araújo, D., Davids, K., & Button, C. (2012). The role of ecological dynamics in analysing performance in team sports. *Current Opinion, 42*(1), 1-10. doi:0112-1642/12/0001-0001/$49.95/0

Ward, P., & Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: The multidimensional nature of expert performance. *Journal of Sport & Exercise Psychology, 25*(1), 93-111

Weigelt, M., Ahlmeyer, T., Lex, H., & Schack, T. (2011). The cognitive representation of a throwing technique in judo experts - Technological ways for individual skill diagnostics in high-performance sports. *Psychology of Sport and Exercise, 12*(3), 231 - 235. doi:10.1016/j.psychsport.2010.11.001

Wein, H. (2007). *Developing Youth Football Players*. Champaign (IL): Human Kinetics.

Williams, A. M., & Davids, K. (1998). Visual search strategy, selective attention, and expertise in soccer. *Research Quarterly for Exercise and Sport, 69*(2), 111-128

Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1993). Cognitive Knowledge and Soccer Performance. *Perceptual and Motor Skills, 76*(2), 579-593. doi:10.2466/pms.1993.76.2.579

Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1994). Visual search strategies in experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport, 65*(2), 127-135

Williams, A. M., Hodges, N. J., North, J. S., & Barton, G. (2006). Perceiving patterns of play in dynamic sport tasks: investigating the essential information underlying skilled performance. *Perception, 35*(3), 317-332. doi:10.1068/p5310

Williams, A. M., & Reilly, T. (2000). Talent identification and development in soccer. *Journal of Sports Sciences, 18*(9), 657-667

Winnick, J. J., Davis, J. M., Welsh, R. S., Carmichael, M. D., Murphy, E. A., & Blackmon, J. A. (2005). Carbohydrate Feedings during Team Sport Exercise Preserve Physical and CNS Function. *Medicine and Science in Sports and Exercise, 37*(2), 306-315

General Discussion

CHAPTER6

The line of research in the current thesis focused on the investigation of cognitive representation units responsible for the execution of manual actions, complex actions, and interactions. The aim was to provide further insights in the cognitive architecture of motor actions. The results of the experiments suggested a further conceptualization of representation units. Thus, the thesis focused on a description of the *granularity of cognitive representation units* in humans LTM. Three movement-related representation units expanded the model of Schack (2010): Basic Interaction Concepts (BICs), Basic Action Concepts (BACs), and Basic Movement Concepts (BMCs).The three movement-related representation units are subject to the similar structuring and dimensioning processes as representation units of complex actions (Schack, 2010). Therefore, the representation units (BICs, BACs, and BMCs) depend on similar functional principles of movement organization. The complex process of action organization aligns such representation units in a hierarchical order, from sensory surface features to functional features in terms of movement organization. In consequence, the representation units can be accessed on an average availability for action execution.

In correspondence to Bernstein's *systems theory* (1967) and Schack’s *cognitive architecture of complex actions*, which suggested a hierarchical control in movement organization, the current approach postulated in this thesis, addresses also the DoF problem. A movement is a function of the systems self-organization of the available DoF into a single functional unit, which is responsible for a specific task. Therefore, higher levels of the nervous system activate lower levels. Lower levels activate synergies described exemplarily as groups of muscles, which execute the movement task

(Bernstein, 1967). An example from the field of linguistics presents a vivid illustration of the mentioned hierarchical control. That illustration puts letters on a level with synergies described in Bernstein’s approach. Letters assemble to a word, which represents the lower architectural level. In turn, words assemble to a sentence, which represents the higher architectural level. According to Bernstein’s systems theory of motor control, Schack (2002, 2010) developed the cognitive architecture of complex motor actions, where four hierarchically structured levels (two representation and two control levels) are responsible for the movement organization and the control of the DoF. These control and representation levels possess different functions and interact with each other.

The following sections discuss the main findings of the current thesis with regard to the cognitive representation units at the three movement-related complexity levels of manual actions, complex actions, interactions. These findings emphasize a hierarchical movement organization. At the end, implications of such findings are discussed with regard to an advanced theory of the cognitive architecture of movement organization.

Cognitive Representations in Manual Actions

Up to now, it seems clear that cognitive mechanisms play a multifaceted functional role in the organization of adaptation processes in humans. Internal models are capable to adjust behavior appropriately to new environmental conditions. However, neurophysiologic studies suggested that other cognitive processes like representations of movement directions are also involved in goal-oriented grasping movements (Georgopoulos, Caminiti, Kalaska, & Massey, 1983). If there is neurophysiologic evidence for the activation of direction-sensitive neurons during grasping movements, then there might be a cognitive representation of movement directions. This cognitive representation of movement directions relates to a certain reference frame (Frank, 1992; 1994). The research question of the experiments described in CHAPTER2 and 3focused on the influence of cognitive representations of movement directions on the adaptation behavior in goal-oriented pointing movement including a distortion of the visual feedback in terms of a left-right reversal. The results delivered evidence for the existence of a cognitive representation of movement directions within human memory. However, there are differences between humans regarding their representation structure of movement directions. There exist two types of cognitive representation of movement directions, *global* and *local* cognitive representation of movement directions. Global cognitive representations signalize an alignment of movement directions towards the cardinal movement directions along the sagittal and horizontal axis. Local cognitive representations of movement directions signalize an alignment of movement directions towards neighboring directions describing differences of 30° between each other. In conclusion, it turns out that a global representation of movement directions leads to functional advantages in adapting towards a distortion of the visual feedback in terms of a left-right reversal (i.e., mirroring along the sagittal axis). The local representation of movement directions seems to be disadvantageous in such a task. Presently it remains speculative whether the reason for the advantage of the global representation schema will be a functional similarity between both (i.e., the representation and the distortion). However, if this were the case, a local representation might facilitate distortions of the visual feedback in terms of small rotations (i.e., 30 or 45° rotation).

Further research needs to clarify this possibility. Nevertheless, the different presentation conditions (i.e., visual or visual-proprioceptive) in the measurement of the cognitive representation of movement directions described in CHAPTER 2 and 3 had an impact on the representation structure. The local representation structure of poor adapters measured in the visual presentation condition excludes the movement directions in the cardinal axes. The measurement of cognitive representation of movement directions in the visual-proprioceptive presentation condition leads to an integration of the cardinal movement directions, but neighboring movement directions joined the cardinal axes. However, both representations were dysfunctional with regard to the selected distortion. Thus, the presentation mode has an impact on the cognitive structure of movement directions. The adaptive variability of movement skills increases in correspondence to the functional organization of cognitive representations of movement directions, which leads to a more elaborated movement execution.

Cognitive Representations in Complex Actions

Various studies investigated the cognitive representations of complex motor actions (e.g., Bläsing, Tenenbaum, & Schack, 2009; Schack & Mechsner, 2006; Weigelt, Ahlmeyer, Lex, & Schack, 2012). The results of such studies showed that a functionally organized memory structure of a certain technique defines the level of expertise of an athlete. This functional organization corresponds to kinematic and dynamic movement features (Heinen & Schack, 2003; Schack, 2003; Schütz, Klein-Soetebier, & Schack, 2009). However, the presented kinematically matched action sequences were in part not from the field of expertise of the observers (i.e., from humanoid robot and a human motor system). The results suggested that the action specific knowledge is not transferable to such a related movement (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005).This open issue formulates the question, how movement expertise relates to the executing motor system.

The current thesis provided evidence in line with the hypothesis formulated in CHAPTER 4 that humans are able to transfer their action-specific knowledge onto a comparable motor system (i.e., humanoid robot). The results suggest such a transfer of action-specific knowledge from the known human motor system onto an unknown artificial, but comparable (in terms of appearance) motor system by the movement experts.

However, robot experts incorporate knowledge about the artificial motor system at an intellectual level (i.e., knowledge about the actuators, DoF of the system, software architecture etc.) into their cognitive representation of the humanoid robot movement. Robot experts integrate their perceptual-motor and their neuro-functional machine representation into a complex representation of the humanoid robot movement. Therefore, cognitive representations of complex actions are composed of all accessible knowledge fragments accessible for a proper action representation. These fragments refer to intellectual and perceptual-motor knowledge, and cumulate in a complex representation of a motor action with regard to the executing motor system.

Cognitive Representations in Interactions

Interactions in sport games are a characteristic and performance-relevant parameter in sport games. Especially, in a soccer-specific environment many interactions involving up to 22 players happen on the pitch. The interactions between players are of relevance for tactical decisions of single players (Höner, 2005). To make proper tactical decisions it seems adequate that players possess functionally organized memory structures about tactical strategies in their LTM. The results of the studies described in CHAPTER 5 delivered evidence that more experienced players possess a functionally organized memory structure of team-specific tactics. Less experienced soccer players do not. In addition, the experiments regarding decision-making and gaze behavior delivered evidence that a functional representation of team-specific tactics enables more experienced soccer players to shift their attention to decision-relevant points of interests. Such a gaze behavior allows them to retrieve the necessary decision-relevant information. That means that the evaluation of the perceived information can start earlier. Thus, a functional memory structure of team-specific tactics facilitates the decision-making process, which leads to an advantage on the pitch in the initiation of adequate complex actions (e.g., sprinting, tackling, passing etc.).

The results presented in CHAPTER 5 delivered evidence for the fact that team-specific tactics are stored in human LTM as functionally organized entities (i.e., afforded tactical behavior of certain match situations). Team-specific tactics in soccer determine the choice for an adequate complex action. The experiments suggest that the way in which LTM organizes team-specific tactics seems to be analogous to the organization of complex actions and movement directions. It seems trivial, but a functional cognitive representation facilitates the hierarchical organization of the decision-making process from perception to action. These experiments delivered first evidence that such a representation level exists in human LTM.

Advances to the Cognitive Architecture of Actions

In general, the essence of such research is not only the effect-oriented vivid description of cognitive representations, but also the necessity to integrate such findings in a complex and descriptive model (Bernstein, 1988). Architectural models describe the process of movement organization based on movement-related and knowledge-based systems. Merely, a few models combine the perspectives of cognitive and movement science with each other in an overarching theory. The cognitive architecture of complex motor actions (Schack, 2002), for instance, is a recent approach to describe the processes of movement organization. This theoretical approach emerges from the perspective of the executive function of the motor system. This proposition of the executive function is already a subject matter of the action theory (Nitsch, 2004).One prerequisite for the movement organization is the anticipation of future movement effects (Bernstein, 1967), which implies the understanding of the movement problem. Thus, humans have to understand the movement tasks and solve the movement problems in a goal-oriented manner (Schack, 2012). One of the main problems is the overcoming of the DoF problem. Therefore, the cognitive system must be able to use the DoF in an optimal way to solve a current movement problem. That is the transformation of the DoF from a manifold system into a controllable system (Bernstein, 1971). However, how is a motor system responsible for the transfer of anticipated movement effects into precise motor actions functioning? Schack (2002, 2012) recommended the separation of different representation levels from each other according to different functional aspects within movement organization, the level of mental representation and the level of sensorimotor representation. Elementary functions (e.g., reflexes) directly connected to reactions on stimulus configurations dominate the level of sensorimotor representation. In contrast, signs and symbols (i.e., mental representations) mediate the movement organization of intentionally guided movements. Schack (2002, 2010) used BACs as a cognitive representation unit (i.e., nodes) of the functional movement organization on the level of mental representation. These building blocks of motor actions complement the functional units on the level of sensorimotor representation. Both representation levels, the effect-oriented goal anticipation of mental representations and the perceptually driven sensorimotor representations constitute the process of movement execution. The representation units at the level of sensorimotor control are not in the focus of the current thesis. It is of mere speculation if GMPs (Schmidt, 1975) or other representation units are stored at such a level. Sensorimotor representations are responsible for the muscle innervation. They possess a direct connection to the representation units at the level of mental representation (i.e., BACs).

In addition to Schack (2002, 2010) the recent thesis discusses two dimensions with regard to mental representations. The vertical dimension of representation units is constrained by their linkage towards the corresponding feature dimensions of the movement. Thus, goal-oriented action effects including their reafferent sensory patterns form the vertical dimension of representation units. The evolved network of action nodes (i.e., representation structure) allows the deduction to feature dimensions of representation units in all three movement categories investigated in this thesis. The focus of the current thesis is on the horizontal dimension of mental representations. The experiments described in the CHAPTERS 2 to 5 highlighted the relevance of cognitive representations for the movement organization of manual actions, complex actions, and interactions. These different movement categories vary on the level of complexity in terms of the integration of more DoF, which leads to different organizational stages. The finding of identical measurement of cognitive representations in all experiments of the current thesis at the different organizational levels of manual actions (movement directions), complex actions (instep kick in soccer), and interactions (team-specific tactics) by selected mental representation units points implicitly at the existence of a horizontal dimension of representation units at the level of mental representation.

A practical example elucidates the problem. Imagine a handball player involved in an offensive situation. That player has to make various decisions in attempting to score. Thus, scoring a goal is the overarching effect, which drives the player’s effort and influences the cognitive processes involved in movement organization. That player tries to control all necessary DoF in a functional manner. First, a tactical decision based on information about teammates and opponents positions drives the activation of tactical concepts, and results in the choice for a shot at the goal. Second, a technical decision based on the defensive action of the direct opponent drives the activation of an adequate technique, and results in a jump shot or a straight shot at the goal. Third, an additional technical decision drives the execution of the chosen technique, and results in direction sensitive hand movement to control the flight path of the ball to overcome the goalkeeper's defense actions. This practical example illustrates the different complexity levels in the decision-making process.

The data presented in the current thesis supports the hypothesis that selective hierarchical processes constrain the cognitive movement organization of cognitive units at the level of mental representation. The cognitive movement organization bases on a hierarchical organization of representation units corresponding to different organizational levels of movement complexity (i.e., in terms of DoF)along a horizontal dimension. Up to now, the cognitive units at the level of mental representation were labeled as BACs (Schack, 2002; 2010), as they focused on the organization of complex actions. Representation units (i.e., concepts) are cognitive groupings of objects and events in terms of the anticipation and realization of action goals (Hoffmann, 1993; Schack, 2010).Cognitive representation units constitute the mediating steps between the anticipated action goal and the solution of a movement problem. In addition to Schack (2002, 2010), cognitive representation units located at the level of mental control and the level of sensorimotor representation(BICs and BMCs) emphasize the broader nature of representation units at the level of mental representation. Of course, representation levels connect the concepts with each other, because they integrate the feature dimensions of the next level. Thus, the network of representation units across organizational levels in the cognitive architecture spans the horizontal dimension(presented in Table 6.1).

Table 6.1

Hierarchical action organization across the levels of mental representation in the cognitive architecture of movements

Level	*Mean*	*Stage*	*Example*
Mental control	Symbols, Strategies	Action organization *Overarching movement features*	Basic Interaction Concepts (BIC)
Mental representation	Representation of complex actions	Action control *Effect-oriented units in motor action organization*	Basic Action Concepts (BAC)
Sensorimotor representation	Perceptual effect representations	Action implementation *Movement adjusting features*	Basic Movement Concepts (BMC)
Sensorimotor control	Functional systems, basic reflexes		

The involvement of different organizational levels (different task complexity) in motor actions is best described by a hierarchical representation schema at the level of mental representation. The different task complexity of the represented world maps on the different representation complexities in the representing world. Thus, the successful participation in complex sport games requires learning things about the represented world. First, a learner needs to establish new sensorial effects about the movement execution. Second, a learner needs to organize these new sensorial effects and acquire new skills. Third, these new skills are context-dependent (i.e., a tactical behavior at various levels). In argumentum e contrario, this means that tactical concepts (e.g., team-specific tactics)determine the choice for an adequate technical behavior (i.e., motor skill), and that the preferred motor skill (e.g., instep kick in soccer)requires a substantial representation of adjustable components (e.g., movement directions) of movement organization. The representation units at different movement-related categories describe hierarchical stages along the horizontal dimension of cognitive representation units. Thereby, the output of the higher-level stages (top-down) is the set of probabilities of the subordinate stages, which are responsible for the selection of effect-appropriate lower-level stages representations (comparable to the MOSAIC model of Wolpert, Doya, & Kawato, 2003). For example, the overarching action effect triggers representations (i.e., tactics, shot, direction) that influence the decision-making process in handball (e.g., shooting at the goal). Moreover, the different representation stages cause each other in a way that one might be an integral component of the other: from the representation of movement directions, via the representation of complex actions to the representation of tactics. The representation units are responsible for action organization (e.g., tactics), action control (e.g., instep kick), and action implementation (e.g., movement directions). The different organizational level provide evidence for a *granularity of mental representations* in relation to movement-related categories. Figure 6.1 illustrates the aforementioned hierarchical composition of representation units.

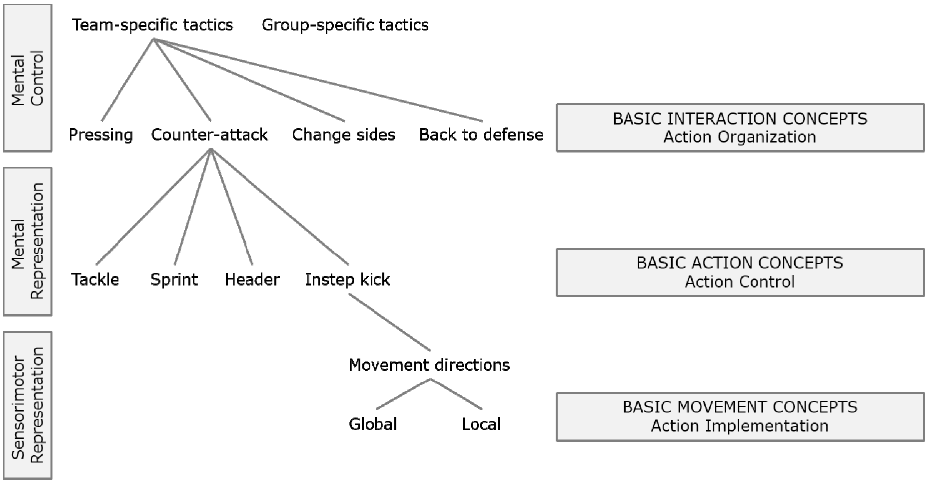

Figure 6.1 Extract from the cognitive architecture of complex actions (Schack, 2010) shows the hierarchical action organization in terms of BICs, BACs, and BMCs across selected representation and execution levels.

The meaning of representations varies in dependence to the embedded context (Goschke & Koppelberg, 1990). Such a process develops similar to the intellectual passage on the way from birth to maturity in stages and substages explaining the changes in perception and thought (Eimas, 1995). Presumably, varieties of examples exist for the different stages, which should be an object of research in further experiments. In this sense, soccer-specific training addresses both, group-specific and individual tactics training ahead of team-specific tactics. Thus, there are hints from practical training experience that a representation of various tactics exists. Thus, according to a slightly compatible example of letters which constitute words and words which constitute sentences, the BMCs (e.g., letters) get meaning through their arrangement by BACs (e.g., words) and BACs get meaning through the arrangement by BICs (e.g., sentence).The apparent discontinuities throughout this development differ in respect to the mental representations and the processes that operate on these representations (Piaget, 1952). In a broader sense, because humans tend to recycle previously acquired knowledge and strategies rather than starting new planning activities (Eisenstadt & Kareev, 1975), new representations evolve from the modification of existing ones.

The current thesis examined the existence of representation units at different representation levels. However, there are also arguments, which emphasize an integration of these representation units into a single representation of a movement representation. Therefore, it is necessary to investigate BICs, BACs, and BMCs at an intrapersonal level. Studies from classical ballet showed that the representation of feature dimension such as movement directions constitute complex movements like "petit pas assemble" and "pirouette en dehors" (Bläsing & Schack, 2012). Moreover, it is interesting for future research projects to investigate certain movements (e.g., a shot at the goal in soccer) by an integration of BICs, BACs, and BMCs. Therefore, a measurement of the cognitive representation should integrate all action relevant movement parameters in terms of complex feature dimensions.

The modeling of expertise is also an issue in the research of artificial intelligence. Kelso (1995) proposed that the dynamic systems theory subsumes aspects of the motor program theory. Similarities in the theoretical approaches assume that inverse and forward models (Wolpert & Kawato, 1998) are able to solve the DoF problem. Similar as in the GMP theory (Schmidt, 1975) a knowledge center is responsible for such processes. The solution for the DoF problem should integrate fixed (invariant parameters like relative timing, relative force, and sequence of action) and flexible (environmental parameters) elements. A schema or equation (i.e., a set of rules) guides the decision process and updates or revises the corresponding motor system. All information relevant for movement execution exists in the environment, and a movement pattern emerges as a function of the ever-changing constraints placed upon it. However, the results of the current thesis deliver evidence that human memory processes states of environmental conditions and integrates these as sensory features in distinct representation units. The structure of representation units develops throughout sustained learning phases, and represents a hierarchical organization in terms of functional movement features. This result exhibits parallels to systems engineering. System engineering uses intermediate representations for the implementation of concepts and strategies (Ford, Bradshaw, Adams-Webber, & Agnew, 1993). The proposed approach of BICs, BACs, and BMCs deliver evidence for a hierarchical, context-related implementation of such representations. It might be interesting to investigate such an idea for systems engineering in more detail by further purposeful research in that area. The focus should be on the involvement of the widely separated neural structures and their participation in category learning, which depends to varying degrees on the category structure itself (Ashby & Ell, 2001). The data presented in the current thesis delivered hints for the identification of the structure of an action-relevant category. At present, it remains speculative that humans might use different neural circuits to establish different types of representation units (Ashby & Ell, 2001, p.209).

References

Ashby, F. G., & Ell, S. W. (2001). The neurobiology of human category learning. *Trends in Cognitive Science, 5*(5), 204-210.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Bernstein, N. A. (1971). Bewegungskontrolle (transl. Motor Control). In T. Kussmann & H. Kölling (Eds.), *Biologie und Verhalten* (pp. 146-171). Bern: Huber.

Bernstein, N. A. (1988). *Bewegungsphysiologie (transl. Movement Physiology)* (Vol. 2). Leipzig: Barth.

Bläsing, B., & Schack, T. (2012). Mental Representation of Spatial Movement Parameters in Dance. *Spatial Cognition & Computation, 12*(2-3), 111-132.

Bläsing, B., Tenenbaum, G., & Schack, T. (2009). The cognitive structure of movements in classical dance. *Psychology of Sport and Exercise, 10*(3), 350-360.

Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex, 15*(8), 1243-1249.

Eimas, P. D. (1995). Categorization in early infancy and the continuity of development. In J. Mehler & S. Franck (Eds.), *Cognition on Cognition* (pp. 289-300). Cambridge: MIT Press.

Eisenstadt, M., & Kareev, Y. (1975). Aspects of human problem solving: The use of internal representations. In D. A. Norman & D. E. Rumelhart (Eds.), *Exploration in Cognition*. San Francisco: Freeman and Company.

Ford, K. M., Bradshaw, J. M., Adams-Webber, J. R., & Agnew, N. M. (1993). Knowledge acquisition as a constructive modeling of activity. *International Journal of Intelligent Systems, 8*(1), 9-32.

Frank, A. U. (1992). Qualitative spatial reasoning about distances and directions in geographic space. *Journal of Visual Languages and Computing, 3*(4), 343-371.

Frank, A. U. (1994). Qualitative spatial reasoning: cardinal directions as an example. *International Journal of Geographical Information Systems, 10*(3), 269-290.

Georgopoulos, A. P., Caminiti, R., Kalaska, J. F., & Massey, J. T. (1983). Spatial coding of movement: A hypothesis concerning the coding of movement direction by motor cortical populations. *Experimental Brain Research, Supplement 7*, 327-336.

Goschke, T., & Koppelberg, D. (1990). *The concept of representation and the representation of concepts in connectionist models*. Bielefeld: Zentrum für interdisziplinäre Forschung.

Heinen, T., & Schack, T. (2003). Movement organization and kinematics in sports: in-group-coherences and inter-subject-differences. In F. Schmalhofer, R. M. Young & G. Katz (Eds.), *Proceedings of the European Conference on Cognitive Science* (pp. 396). New York: Lawrence Erlbaum Associates.

Hoffmann, J. (1993). *Vorhersage und Erkenntnis (transl. Prediction and Awareness)*. Göttingen: Hogrefe.

Höner, O. (2005). *Entscheidungshandeln im Sportspiel Fußball – Eine Analyse im Lichte der Rubikontheorie (transl. Decision-making in sport game soccer - An analysis in terms of Rubicon-Theory)*. Schorndorf: Hofmann.

Kelso, J. A. S. (1995). *Dynamic patterns - The self-organization of brain and behavior*. Cambridge: MIT Press.

Nitsch, J. R. (2004). Die handlungstheoretische Perspektive: ein Rahmenkonzept für die sportpsychologische Forschung und Intervention (transl. The action-oriented perspective: A framework for research in sportpsychology and intervention). *Zeitschrift für Sportpsychologie, 11*(1), 10-23.

Piaget, J. (1952). *The Origins of Intelligence in Children*. New York: Norton & Co.

Schack, T. (2002). *Die kognitive Architektur komplexer Bewegungen - modelltheoretische und experimentelle Zugänge zu einer integrativen Bewegungswissenschaft (transl. The Cognitive Architecture of Complex Motor Actions)*. [Habilitation treatise]. Cologne: German Sports University.

Schack, T. (2003). The relationship between motor representation and biomechanical parameters in complex movements: Towards an integrative perspective of movement science. *European Journal of Sport Science, 3*(2), 1-13.

Schack, T. (2010). *Die kognitive Architektur menschlicher Bewegungen – Innovative Zugänge für Psychologie, Sportwissenschaft und Robotik (transl. The cognitive architecture of human movements - innovative approaches to psychology, sport science, and robotic)*. Aachen: Meyer & Meyer.

Schack, T. (2012). Measuring mental representations. In G. Tenenbaum, R. C. Eklund & A. Kamata (Eds.), *Handbook of Measurement in Sport and Exercise Psychology* (Vol. 1, pp. 203-214). Champaign, Illinois: Human Kinetics.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. *Neuroscience Letters, 391*(3), 77-81.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*(4), 225-260.

Schütz, C., Klein-Soetebier, T., & Schack, T. (2009). Modeling of biomechanical parameters based on LTM structures. In H. Ritter, G. Sagerer, R. Dillmann & M. Buss (Eds.), *Human Centered Robot Systems. Cognition, Interaction, Technology.* (pp. 161-171). Berlin: Springer.

Weigelt, M., Ahlmeyer, T., Lex, H., & Schack, T. (2011). The cognitive representation of a throwing technique in judo experts - Technological ways for individual skill diagnostics in high-performance sports. *Psychology of Sport and Exercise, 12*(3), 231-235.

Wolpert, D. M., Doya, K., & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358*(1431), 593-602.

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks, 11*(7-8), 1317-1329.

Summary

CHAPTER 7

The perspectives described in the current thesis are restricted to considerations about the control of voluntary movements at the level of mental representation. Every detailed and structured introspection or self-monitoring is unable to reflect the adequate choice of innervated muscles, the power of needed force, and the temporal dynamics to execute a task. The question is which cognitive mechanisms enable humans to execute voluntary movements and how they are accessed. Several scientific theories and models described the cognitive organization of voluntary movements starting approx. 150 years ago. Hereafter, it seemed obvious that the representation of only muscle forces or joint velocities is not a feasible representation format for the control of voluntarily executed movements. In fact, a promising approach postulates the existence of cognitive representations. Cognitive representations might constitute a plausible connection between the to-be-produced environmental effects and the actual (muscular managed) control of the own body. The current thesis describes research results delivered from experiments, which investigated cognitive representations at three different movement-related complexity levels: manual actions (1), complex actions (2), and interactions (3).

The aim of CHAPTERS 2 and 3 was to determine whether relevant cognitive representation structures (i.e., *Basic Movement Concepts*) influence a sensorimotor adaptation process in manual actions. To this end, participants were confronted with a pointing task including a sensorimotor adaptation towards a visual distortion in terms of a left-right reversal. In addition, the experiments investigated participant's representation of movement directions. The results revealed that skilled adapter's representation of movement directions differs from poor adapters. The differences between the representation structures elucidated the qualitative differences between the sensorimotor adaptation abilities of the participants. Thus, the cognitive representation structure facilitates or impedes the sensorimotor adaptation towards a certain distortion. This result delivered evidence for the existence of *Basic Movement Concepts* responsible for the voluntary movement execution at the level manual actions.

The aim of CHAPTER 4 was to verify whether relevant cognitive representation structures control a complex motor action, and which information is accessed in such a representation (i.e., Basic Action Concepts). The hypothesis was that a cognitive representation structures are active during the observation of an unknown motor system (i.e., humanoid robot). To this end, participant's representation of the instep kick in soccer was measured by the presentation of BACs of either a human or a humanoid robot movement. The results delivered evidence for an expertise-dependent representation structure of complex actions. Furthermore, the results revealed a domination of the perceptual-motor knowledge of the human motor system by soccer experts. In contrast, humanoid robot experts accessed functional features of the technical system in addition to their perceptual-motor knowledge about the movement. Thus, their perceptual-motor and neuro-functional machine representation is integrated into a cognitive representation of the humanoid robot movement. Accordingly, BACs control the movement execution of complex actions, and integrate information from all accessible knowledge sources.

The aim of CHAPTER 5 was to determine the core elements for the coordination of interactions (i.e., team-specific tactics) in sport games. For this purpose, the cognitive representation of team-specific tactics was measured for different expertise levels by the presentation of twelve diverse match situations. The results showed that soccer experts, in contrast to soccer novices, possess a functional representation of team-specific soccer tactics. Moreover, this functional representation structure enabled soccer experts to shift their attention precisely to the relevant points of attraction in a match situation. Thus, soccer experts are able to decide faster for an adequate team-specific tactic in soccer. The results delivered evidence for the existence of cognitive representations at the level of interactions, which have a direct influence on performance relevant parameters.

The work presented in this thesis investigated cognitive representations responsible for the execution of movements at the level of manual actions, complex actions, and interactions. The representation structures at all the levels of different complexity revealed similarities regarding the organization of the corresponding representation units. The data of the current thesis proposes a hierarchical order formation at the level of mental representations in the cognitive architecture of complex actions. This order formation distinguishes the stages of action organization (e.g., Basic Interaction Concepts), action control (e.g., Basic Action Concepts), and action implementation (e.g., Basic Movement Concepts) from each other. CHAPTER 6 discusses the findings, and expands the approach of the cognitive architecture of complex actions with regard to the granularity of cognitive representations in actions.

Acknowledgments

DANKSAGUNG

I wrote the current thesis in the Research Group Neurocognition and Action of the Institute of Sports Science at Bielefeld University under supervision of *Prof. Dr. Thomas Schack*.

I thank the Research Group Neurocognition and Action as well as the Research Institute for Cognition and Robotics (CoR-Lab) and the Excellence Cluster Cognitive Interaction Technology (CITEC) for providing me with an excellent research environment.

Especially, I say thank you to my *"Boss" Prof. Dr. Thomas Schack*. Your long-lasting scientific support, your interest in my personal development, and the way of your supervision during my PhD became a fundamental part of myself.

Thank you *Prof. Dr. Andreas Knoblauch* and *Prof. Dr. Yaochu Jin* for your support through Honda Research Institute Europe. I gratefully acknowledge the financial support from Honda Research Institute Europe, CITEC, and the Research Group Neurocognition and Action - Biomechanics.

I thank you, *Prof. Dr. Matthias "Marty" Weigelt*, very much, not only for sharing your scientific experience (e.g., specifically for your immediate, critical, and elaborate feedback), but also for your very helpful counseling in the scientific community (e.g., at countless conferences).

I thank my recent *(e.g., Ludwig Vogel, Christian Seegelke, Christoph Schütz, Kai Essig, Dietmar Pollmann, Bettina Bläsing, Jan Westerholz, Arthur Steinmann, Borghild Figge)* and former *(Breanna Studenka, Tino Stöckel, Iris Güldenpenning, Paola Reißig)* colleagues of the Research Group Neurocognition and Action. You are representatives of the critical, constructive, and pleasant working atmosphere within our group.

Thanks to you, *Philip Furley*, for proofreading the current thesis.

It is of very high importance for me to thank my parents: Friedrich-Karl and Sigrid Lex. Especially I thank them for their unconditional support throughout my entire life. Without their love, help, and advice I would have never ever made it through this long-lasting academic process.