MENTAL REPRESENTATION AND LEARNING IN COMPLEX ACTION

A PERCEPTUAL-COGNITIVE VIEW ON MENTAL AND PHYSICAL PRACTICE

MENTAL REPRESENTATION AND LEARNING IN COMPLEX ACTION

A PERCEPTUAL-COGNITIVE VIEW ON MENTAL AND PHYSICAL PRACTICE

Kumulative Dissertation
zur Erlangung des akademischen Grades
doctor rerum naturalium (Dr. rer. nat.)
vorgelegt der Fakultät für Psychologie und Sportwissenschaft
der Universität Bielefeld
von Cornelia Frank

Bielefeld im September 2014

1. Gutachter

Prof. Dr. Thomas Schack [1,2,3]

2. Gutachter

Prof. Dr. Thomas Heinen [4]

Betreuer

Prof. Dr. Thomas Schack [1,2,3]

Dr. William Land [5]

[1] Fakultät für Psychologie und Sportwissenschaft,
Abteilung Sportwissenschaft,
Neurokognition und Bewegung - Biomechanik,
Universität Bielefeld

[2] Exzellenzcluster Kognitive Interaktionstechnologie (CITEC),
Universität Bielefeld

[3] Research Institute for Cognition and Robotics (CoR-Lab),
Universität Bielefeld

[4] Fachbereich Erziehungs- und Sozialwissenschaften,
Institut für Sportwissenschaft,
Sozialwissenschaften des Sports,
Universität Hildesheim

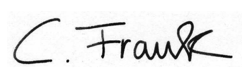
[5] Department of Kinesiology, Health, & Nutrition,
University of Texas at San Antonio
United States of America

EHRENWÖRTLICHE ERKLÄRUNG ZUR DISSERTATION

Sehr geehrte Damen und Herren,

hiermit erkläre ich an Eides statt, dass ich die Dissertation mit dem Titel „Mental representation and learning in complex action: A perceptual-cognitive view on mental and physical practice“ selbstständig 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 habe ich als solche gekennzeichnet. Ich versichere außerdem, dass ich die vorliegende Dissertation nur in diesem und keinem anderen Promotionsverfahren eingereicht habe und dass diesem Promotionsverfahren keine endgültig gescheiterten Promotionsverfahren vorausgegangen sind.

Bielefeld, den 22. September 2014



Cornelia Frank

DANKSAGUNG

Meinem Professor Thomas Schack: Du hast mich sowohl gefördert als auch gefordert, hast mir Freiräume gegeben, um zu gestalten, um meinen Weg zu gehen, und mich von Zeit zu Zeit in Schranken gewiesen, so dass ich nie vom Weg abkam. Danke!

Meinem Mentor Billy Land: Deine Tür stand immer offen, du hattest immer ein offenes Ohr für meine Fragen, und warst ein enger Begleiter auf meinem Weg in die Wissenschaft. Danke!

Meinem Kollegen Christoph Schütz: Deine Hilfe in technischen, mathematischen, statistischen wie auch praktischen Fragen war mir eine Hilfe von unschätzbarem Wert. Danke!

Der Arbeitsgruppe Neurokognition und Bewegung – Biomechanik: Für den Alltag hier mit euch in Forschung und Lehre. Danke!

Den Studierenden: Für euren Einsatz im Rahmen eurer Abschlussarbeiten und für euren Einsatz als Teilnehmer an den einzelnen Untersuchungen. Danke!

Dem Exzellenzcluster Kognitive Interaktionstechnologie (CITEC): Das Internationale und Interdisziplinäre hat diese Zeit zu etwas sehr Besonderem gemacht. Danke!

Der Deutschen Forschungsgemeinschaft (DFG): Diese Art der Finanzierung hat es mir ermöglicht, mich voll und ganz auf meine Forschung zu konzentrieren. Danke!

DANKSAGUNG

Meinem Jörn: Du warst immer da, hast die schweren Zeiten mit getragen, und bist in den guten Zeiten mit geflogen. Alles Weitere lässt sich nicht in Worte fassen. Danke!

Meinem Vater Werner: Als ich klein war, hast du mir den Weg zum Turnen, zum Sport, und damit zur Bewegung aufgezeigt. Und als ich groß war, hast du mich diesen, meinen eigenen Weg gehen lassen. Danke!

Tom: Mit deiner Hilfe habe ich den Weg zurück in die Wissenschaft gefunden und die nötige Motivation entlang des Weges aufrecht erhalten können. Danke!

Joe: Während unserer Gespräche erinnerte ich mich an das, was mich interessierte, das, was mich faszinierte, und fand so den Weg zurück in die Wissenschaft und hin zur kognitiven, von Disziplinen unabhängigen Perspektive auf den sich bewegenden Menschen. Danke!

Dem lebendigen Geist.

Für meine Familie, und insbesondere für meine Mutter.

The present work is based on the following manuscripts:

CHAPTER 2

is based on

Frank, C., Land, W. M., & Schack, T. (2013). Mental representation and learning: The influence of practice on the development of mental representation structure in complex action. *Psychology of Sport and Exercise, 14*, 353-361.

CHAPTER 3

is based on

Frank, C., Land, W. M., Popp, C., & Schack, T. (2014). Mental representation and mental practice: Experimental investigation on the functional links between motor memory and motor imagery. *PLoS ONE, 9*, e95175.

CHAPTER 4

is based on

Frank, C., Land, W. M., & Schack, T. (under review). Perceptual-cognitive changes during motor learning: The influence of mental and physical practice on mental representation, gaze behavior, and the performance of a complex action. *Psychological Research.*

SUMMARY

An extraordinary and extremely sophisticated capability of human beings is that of performing motor actions in a goal-directed manner. Consider, for example, skilled golfers proficiently performing golf putts under various constraints such as putts from various distances, putts on different greens, or putts comprising diverse breaks. How did they arrive at performing in such a sophisticated, adaptive and yet stable, manner?

The two most common means to learn a motor action are through physical and mental practice. Both types of practice have shown to lead to performance improvements, and in this sense, to promote motor learning. However, motor learning as induced by mental and physical practice has rarely been approached with a specific focus on the perceptual-cognitive, representational level of action organization. To date, research has yet to systematically investigate the influence that mental and physical practice have on the motor action system in terms of the development of mental representation of complex action. The present work seeks to bridge this particular research gap. Specifically, motor learning and the influence of two types of practice, mental practice (i.e., covert practice) and physical practice (i.e., overt practice), are approached from a perceptual-cognitive, architecture based point of view. As such, the present work provides insights into the perceptual-cognitive adaptations that occur within the motor action system during early skill acquisition.

In short, the theoretical contributions of the present work entail elaborations on the distinct influence of mental and physical practice on the motor action system, and the level of mental representation in particular, drawing back on the cognitive action architecture approach. From an empirical standpoint, three learning studies are described that shed further light on motor learning and mental practice from a perceptual-cognitive, representation-based point of view.

Chapter 1 provides an overview of the theoretical perspectives and empirical evidence relating to motor learning and mental practice, with a particular focus on perceptual-cognitive approaches and the functional role of mental representation. Accordingly, the cognitive action architecture approach is described and the potential influence of mental and physical practice within the levels of action organization is sketched, followed by an outline of the purpose of the present work.

Chapter 2 explores the development of one's mental representation of a complex action during motor learning. In the study presented, the question was examined whether the mental representation structure of a complex action changes over the course of practice, and whether this change reflects a development toward a more elaborate and functional structure, such as that of an expert. Together with improvements in putting performance, mental representations of the putt were found to change with practice, developing toward more functional ones. Specifically, mental representation structures of the practice group became more similar to a golf expert structure over the course of practice, reflecting distinct phases of the putting movement (i.e., preparation, forward swing, and impact). Instead, mental representation structures of the (no practice) control group did not change and remained dissimilar in comparison to an expert structure. Thus, this study shows that, along with improvements in (overt) performance, the (covert) mental representation of a complex action develops as a result of practice.

Chapter 3 provides further insights into the development of one's mental representation of a complex action according to type of practice, with a particular emphasis on mental practice. Accordingly, the question was investigated whether mental representation structure of a complex action changes as a result of both mental and physical practice as well as a combination of both, and whether the changes reflect a development toward a more elaborate and functional structure. In line with findings from study one, mental representations of the putt developed over the course of practice. Interestingly, mental practice, either solely or in combination with physical practice, led to even more elaborate representations compared to physical practice alone. Specifically, mental representation structures of the groups practicing mentally became more similar to a functional structure, thereby reflecting well the functional phases of the putting movement, whereas those of the physical practice group revealed less development toward a functional structure. Furthermore, putting performance improved over the course of practice, reflecting the well-known pattern of magnitude of improvement according to type of practice. Specifically, combined mental and physical practice was most effective, followed by physical practice, mental practice and no practice (i.e., combined practice > physical practice > mental practice > no practice). Statistically, the combined practice group proved more effective than mental practice only and no practice with respect to performance. Hence, findings from the first study were replicated such that, along with improvements in performance, mental representation of a complex action develops as a result of practice. More importantly, however, according to the results of the second study, mental practice added to the development leading to even more elaborate representations. Notably, these (covert) changes do not seem to transfer one-to-one to the (overt) motor output.

Chapter 4 further explores the perceptual-cognitive background of performance changes that occur within the motor action system as a result of mental and physical practice, thereby providing insights into both mental representations and gaze behavior during complex action. Accordingly, the question was investigated whether mental representation structure of the putt and gaze behavior during putting changes with both physical and combined mental and physical practice, and whether the changes reflect a functional development. Similar to findings of study two, combined mental and physical practice led to more developed representation structures of the putt compared to physical practice alone. As an extension, combined practice as well led to more elaborate gaze behavior prior to execution of the putt. Specifically, final fixations prior to the onset of the putting movement were longer after practice for the group practicing mentally in addition to physical practice in comparison to the control group. This was not the case for the group practicing physically only. Instead, putting performance improved similarly in both practice groups over the course of practice. Thus, the results of study three once more indicate that it is the mental component of the practice that leads to more developed representation structures and more functional gaze behavior. However, similar to study two, these (covert) changes do not become evident on (overt) motor output.

Chapter 5 summarizes the key findings of the three learning studies and discusses them with recourse to the cognitive action architecture approach to motor learning and mental practice. In particular, based on the findings of the present work, the differential influence of mental and physical practice on action organization within the motor action system is discussed, followed by an outline of both limitations and prospects for future research. Altogether, this body of work clearly demonstrates that motor learning by mental and physical practice is associated with perceptual-cognitive adaptations within the motor action system and with functional changes in mental representation structures of complex action in particular, and it furthermore indicates that mental and physical practice differ in their influence on the different levels of action organization.

TABLE OF CONTENTS

1 GENERAL INTRODUCTION

1.1 Motor learning 03

1.1.1 Intelligent systems and motor learning 03

1.1.2 Theoretical perspectives on motor learning 04

1.2 Mental practice and motor learning 10

1.2.1 Mental practice and its influence on the motor action system 10

1.2.2 Theoretical perspectives on mental practice 13

1.3 Mental representation, motor learning and mental practice 17

1.3.1 Empirical approaches to motor learning and mental practice 17

1.3.2 Evidence on mental representation of complex action across skill levels 22

1.3.3 Evidence on mental representation of complex action and motor learning 24

1.3.4 Evidence on mental representation of complex action and mental practice 25

1.4 The cognitive action architecture approach to motor learning 26

1.4.1 Hierarchical organization of actions 26

1.4.2 Mental representation and the organization of actions 29

1.4.3 Motor learning and the modification of mental representation 30

1.4.4 Mental practice and the modification of mental representation 31

1.5 Purpose of the present work 32

1.5.1 Mental representation and its development with mental and physical practice 32

1.5.2 Aims 38

1.5.3 Research questions 39

1.5.4 Predictions 40

2 PHYSICAL PRACTICE AND THE DEVELOPMENT OF MENTAL REPRESENTATION STRUCTURE

Abstract 45

2.1 Introduction 47

2.2 Methods 52

2.3 Results 58

2.4 Discussion 64

3 MENTAL PRACTICE AND THE DEVELOPMENT OF MENTAL REPRESENTATION STRUCTURE

Abstract 73

3.1 Introduction 75

3.2 Methods 80

3.3 Results 87

3.4 Discussion 98

4 MENTAL AND PHYSICAL PRACTICE, THE DEVELOPMENT OF MENTAL REPRESENTATION STRUCTURE AND GAZE BEHAVIOR

Abstract 109

4.1 Introduction 111

4.2 Methods 117

4.3 Results 126

4.4 Discussion 136

5 GENERAL DISCUSSION

5.1 Key findings 147

5.2 Implications 149

5.2.1 The adapting motor action system 149

5.2.2 Mental representation and its development with mental and physical practice 151

5.3 Limitations and prospects 167

5.4 Conclusions 173

REFERENCES 179

FURTHER SCIENTIFIC CONTRIBUTIONS 197

TABLES

Table 1.1	*Levels of action organization*	27
Table 2.1	*Design of study 1 including three test days and an acquisition phase*	55
Table 2.2	*Descriptive statistics for performance variables for the practice group*	60
Table 3.1	*Design of study 2 including three test days and an acquisition phase*	83
Table 3.2	*Degrees of change in adjusted rand indices over the course of the study*	95
Table 4.1	*Basic action concepts (BACs) of the golf putt*	119
Table 4.2	*Design of study 3 including three test days and an acquisition phase*	121
Table 4.3	*Descriptive statistics for performance variables for each of the groups*	127

FIGURES

Figure 1.1	*The levels of action organization during early stages of motor learning*	35
Figure 2.1	*Mean radial error for the practice group during acquisition phase*	59
Figure 2.2	*Mean group dendrograms of the practice and the control group at pre-test*	61
Figure 2.3	*Mean group dendrograms of the practice group at post- and retention-test*	62
Figure 2.4	*Mean group dendrograms of the control group at post- and retention-test*	64
Figure 3.1	*Mean group dendrograms of the mental practice group*	89
Figure 3.2	*Mean group dendrograms of the combined practice group*	91
Figure 3.3	*Mean group dendrograms of the physical practice group*	92
Figure 3.4	*Mean group dendrograms of the control group*	94
Figure 3.5	*Mean radial error from pre-test to post- and retention-test*	96
Figure 3.6	*Bivariate variable error from pre-test to post- and retention-test*	97
Figure 4.1	*Mean radial error from pre-test to post- and retention-test*	128
Figure 4.2	*Bivariate variable error from pre-test to post- and retention-test*	129
Figure 4.3	*Mean group dendrograms of the combined practice group*	131
Figure 4.4	*Mean group dendrograms of the physical practice group*	132
Figure 4.5	*Mean group dendrograms of the control group*	133
Figure 4.6	*Mean quiet eye duration from pre-test to post- and retention-test*	135
Figure 5.1	*The influence of physical practice on the motor action system*	155
Figure 5.2	*The influence of mental practice on the motor action system*	156

1 GENERAL INTRODUCTION

1.1 Motor learning

1.1.1 Intelligent systems and motor learning

To be able to perform goal-directed actions is an extraordinary and extremely sophisticated capability of human beings. Imagine, for instance, expert golfers skillfully performing golf putts under various constraints: putts from long as well as short distances, putts on slower and on faster greens, or putts comprising larger and smaller breaks. How did they learn to perform in such a sophisticated, adaptive and yet stable manner? What kinds of overt and covert changes occurred that allowed for this extraordinary capability to perform such complex tasks? More general, how does the human motor action system learn to adequately solve a motor task in any given situation? The human body is comprised of the brain, bones, joints, ligaments, tendons, muscles, and other components. These components, when working together in an appropriate fashion, allow for movement (e.g., a putt in golf), and thus, for the attainment of an intended goal (e.g., sinking the ball into the hole). But, how do these components – the brain, bones, joints, muscles – become an entity that allows for goal-directed, well-coordinated movement?

Intelligent systems in general and intelligent action in particular are fundamental issues in cognitive science (e.g., Abrahamsen & Bechtel, 2012; Pfeifer & Bongard, 2007). To understand how intelligent systems learn to adequately act in a given environment with respect to a particular task, thereby permanently adapting, is of particular relevance to cognitive science disciplines such as psychology, biology, and computer science, to name just a few (e.g., Engel, Maye, Kurthen, & König, 2013; Pacherie, 2012; Wolpert, Diedrichsen, & Flanagan, 2011). In general, the potential to perform a motor action reflects the capability of an individual to attain an intended effect by way of a given behavior in a given situation (i.e., person-environment-task constellation; e.g., Nitsch, 2004, 2009; Seiler, 2000). This capability changes and develops with practice and experience, transitioning from an unskilled into a skilled motor action (e.g., Magill, 2011; Meinel & Schnabel, 2007; Schmidt & Lee, 2011; Schmidt & Wrisberg, 2008). That is, when being performed repeatedly, the planning and the execution of motor actions are being refined within a particular person-environment-task constellation, which in turn results in a refined interplay of the agent's perception, cognition, and action in a given situation. Accordingly, the objective of motor learning is the development and the adaptation of the human motor action system.

To this extent, learning is vital for any action system to become intelligent, as it allows action systems to both refine and widen their action repertoire and thus to interact with the environment in a more and more ingenious and adaptive fashion. Interestingly, despite growing research interest, advancing our understanding of intelligent systems' actions remains a significant endeavor to this day, especially in view of prospective applications in various settings such as robotics, psychology, sports, and rehabilitation. For instance, the implementation of artificial intelligence and the development of intelligent interactive technical platforms such as robots, which are to assist humans while navigating smoothly within a given environment, require a thorough understanding of natural, intelligent forms of action and their acquisition, respectively (e.g., De Klein, Kachergis, & Hommel, 2014; Di Nuovo, Marocco, Di Nuovo, & Cangelosi, 2013; Pfeifer & Bongard, 2007; Schack & Ritter, 2009, 2013).

1.1.2 Theoretical perspectives on motor learning

To learn how to solve a motor problem, that is how to perform well-coordinated motor action such that it serves to attain intended effects within a given environment, is a major issue of human life. According to Bernstein (1947, 1967), motor control and learning are centered around finding suitable solutions to a particular motor problem. In this sense, the process of learning a motor action reflects more and more elaborate problem solving. In general, researchers agree upon the changing nature of the learning process from unskilled to skilled action (e.g., Anderson, 1982, 1995; Fitts, 1964; Fitts & Posner, 1967; Gentile, 1972; Meinel & Schnabel, 1987): during early motor learning, the agent must solve an entirely unfamiliar motor task, attempting to find an appropriate solution for a specific motor problem (e.g., *cognitive stage*: Fitts & Posner, 1967; *Entwicklung der Grobkoordination*: Meinel & Schnabel, 1987), whereas, during later learning, the motor action that serves to solve the motor problem at hand is being refined based on prior experience (e.g., *associative stage* and *autonomous stage*: Fitts & Posner, 1967; *Entwicklung und Stabilisierung der Feinkoordination*: Meinel & Schnabel, 1987).

The issue of motor learning has a long-standing tradition (e.g., Adams, 1987; Summers, 2004), during which researchers in the field have been trying to find suitable answers to the basic question regarding the underlying mechanisms of motor control and learning. Although a number of theories on motor learning exist to date, the specific mechanisms of learning a motor action are still a matter of debate (for an overview, see e.g., Hodges & Williams, 2012; Magill, 2011; Schmidt & Lee, 2011). In general, two main approaches to the basic mechanisms of motor learning can be distinguished: central (i.e., cognitive) and peripheral (i.e., ecological) approaches, also known as the motor approach and the action approach to motor control and learning (e.g., Meijer & Roth, 1991). In addition to these two camps reflecting two distinct positions, perceptual-cognitive approaches as an integrative perspective on motor learning are introduced in the following.

1.1.2.1 Central perspective on motor learning

A fundamental assumption of central or cognitive approaches to motor learning is the idea that movements are internally represented (e.g., *motor program*: Keele, 1968; *schema*: Schmidt, 1975; for an overview, see e.g., Ivry, 1994; Wiemeyer, 1994a, 1994b)[1]. Specifically, information is being processed and stored in some representational format as a result of movement execution, and in turn influences subsequent movement execution. While skilled motor action is thought to rely on well-developed representations (or motor programs or schemas, respectively), motor learning, according to central approaches, is a consequence of the permanent

[1] The concept of memory is not introduced explicitly in the following, as it does not directly add to the purpose of the work at hand; for more details on declarative/ procedural memory, see chapter 2.1 as well as e.g., Anderson, 1982; Johnson, 2012; for more details on memory in general, see e.g., Tulving & Craik, 2000)

refinement of representations, resulting in more appropriate representations and guiding movement execution in an increasingly reliable manner.

To illustrate, a seminal prescriptive account of motor learning, emerging from the traditional information processing perspective, is the *schema theory of discrete motor learning* (Schmidt, 1975). Originating from the general idea of schemas (Bartlett, 1932; Head, 1926), schemas of motor action can be understood as abstract rules or generalizations that are stored in memory and guide motor actions (Schmidt, 1975). Continuing the idea of two independent memory states (i.e., *perceptual and memory trace*; Adams, 1971), Schmidt (1975) suggested a *recall schema* and a *recognition schema* that guide motor actions. While the recall schema is concerned with movement production, and especially with the selection of parameter values for a particular action, the recognition schema is concerned with movement evaluation, and especially with the estimation of sensory consequences that arise from the action that has been executed. In other words, the recognition schema holds relational information about the motor output and corresponding sensory consequences, whereas the recall schema holds relational information about selected parameters and the corresponding motor output (e.g., McCracken & Stelmach, 1977; Newell & Shapiro, 1976). Furthermore, the concept of *generalized motor programs* (GMP) is essential to Schmidt's theory. According to Schmidt (1975), a given GMP holds information of a particular class of motor actions and as such allows for the common representation of a class of variations of a motor action (i.e., one-to-many relation as opposed to one-to-one relation; e.g., Adams, 1971). This class of motor actions has in common invariant features (e.g., relative force and relative timing), while set parameters (e.g., absolute force and absolute time) serve as means to scale a specific motor action (for a review, see e.g., Schmidt, 1985). Motor learning is thus associated with the evolution of abstract rules and thus schema formation, meaning that practice leads to better developed schemas which, in turn, allow for more stable performance of a motor action. Specifically, motor learning in the light of schema theory is associated with refinement of both the recall and the recognition schema, and thus with more elaborate movement production and evaluation. One major critique of this motor learning theory is that the mere process of schema formation is not well developed and it remains unclear how schemas evolve (e.g., Newell, 1991). Although some major limitations of the schema theory such as schema formation have become apparent over time (e.g., Newell, 2003; Schmidt, 2003; Shea & Wulf, 2005; Sherwood & Lee, 2003), this theory still prevails among cognitive accounts of motor control and learning.

In sum, central approaches to motor learning provide cognitive, memory-based explanations, assuming some form of representation that changes over the course of learning (e.g., Adams, 1971; Anderson, 1982; Fitts & Posner, 1967; Schmidt, 1975). Instead of focusing on the peripheral relation between the person and the environment in explaining motor learning (for details on peripheral approaches, see next chapter), cognitive approaches focus on the representation that is stored centrally and which changes over the course of learning.

1.1.2.2 Peripheral perspective on motor learning

Peripheral or ecological approaches represent a more recent view on motor learning, thereby challenging the traditional cognitive view. From a peripheral point of view, motor control and learning are approached by focusing on the reciprocal relation between the person and the environment. Originating from the *theory of direct perception* (Gibson, 1977, 1979), ecological approaches assume a direct relationship between perception and action (i.e., *perception-action coupling*), thereby dissociating from representational accounts (e.g., Michaels & Beek, 1995). Motor action, in this sense, resides in the direct relation of the person and the environment (e.g., Turvey, 1991; Turvey & Kugler, 1984). Central to this approach are both invariants and affordances. *Invariants* are higher-order characteristics that are permanently available despite any transformations related to the person and the environment in a given situation (e.g., for golf putting: the green, the hole, the putter). *Affordances* reflect the opportunities for a particular action, as perceived by a person in a given environment, and as such guide motor action. Affordances can be objective (e.g., for golf putting: the surface of the green invites to putt) or subjective (e.g., for golf putting: the putt and its success depend on the person's capability to identify the optimal target line; e.g., Davids, Button, & Bennett, 2008). The characteristics of the person in her/ his particular environment and the perceived affordances (i.e., possibilities to act) therein result in the realization of a particular affordance (i.e., motor action). In turn, during the realization, thus while acting, the person perceives her-/ himself in her/ his environment accordingly. From this performer-environment relationship perspective, the interaction of the performer and the environment becomes more elaborate with practice such that the performer becomes better able to attune to higher order invariants. Accordingly, practice results in the setting up of direct perception-action relations. Thus, motor learning reflects the growth and the refinement of the perception-action coupling that guides the realization of affordances (i.e., motor action). In other words, motor learning is considered as the establishment of laws for an elaborate coupling of perception and action (Newell, 1991; Schmidt & Fitzpatrick, 1996).

Related to this view is the *dynamical systems approach* to motor action (e.g., Davids et al., 2008; Glazier, Davids, & Bartlett, 2003; Kelso, 1981, 1995; Walter, Lee, Sternad, 1998). Originating from the areas of mathematics and physics, the approach aims at identifying formal descriptions (i.e., rules) which can describe behavior of complex dynamical systems in space and time. The basic idea is that, based on dynamics of the system and its sub-systems, *self-organization* leads to order. According to this approach, motor action emerges from the interaction of and the coordination between various sub-systems of the human motor action system (e.g., the perceptual system and the skeletomuscular system). This emergence of motor action is seen as a result of self-organizing processes. Of particular importance to this approach are *attractors*. Attractors are tendencies to coordinate the various components of the system in order to achieve stable coordination patterns (for types of attractors, see e.g., Beek, Schmidt, Morris, Sim, & Turvey, 1995). In other words, when being in an attractor state, order appears (i.e., *dynamic stability*: Kelso, 1981; *stability-variability paradox*: Handford, Davids, Bennett, & Button, 1997). By way of self-organization, attractor states emerge and disappear, depending on changes of the person and the environment. These changes, and as such the re-establishment of order, are dependent on factors limiting the interaction of the individual in her/ his environment regarding a particular task (i.e., *constraints*). According to Newell (1986), there are three main classes of constraints: organismic (e.g., in the case of golf putting: height of the golfer), environmental (e.g., the quality of the green), and task constraints (e.g., the size of the hole), that influence both stability and variability, and as such guide the emergence of motor action. Motor learning, according to dynamical systems theory, is reflected by the changes in and the acquisition of dynamics, resulting from elaborating the perceptual-motor workspace, and leading to improved self-organization and thus refined coordination patterns (e.g., Davids, Renshaw, Pinder, Adaújo, &Vilar, 2012; Mitra, Amazeen, & Turvey, 1998; Newell, Mayer-Kress, & Liu, 2001).

Any prescriptive account, such as a centrally stored representation of the motor action in memory, is not discussed, neither in ecological nor in dynamical systems approaches to motor learning. Rather, the performer-environment relationship is considered the most appropriate level of analysis in order to approach motor learning (e.g., Williams, Davids, & Williams, 1999).

1.1.2.3 Perceptual-cognitive perspective on motor learning

More recently, perceptual-cognitive approaches have received growing research interest in the area of motor control and learning (e.g., *theory of anticipative behavioral control*: Hoffmann, 1993; *theory of event coding*: Hommel, Müsseler, Aschersleben, & Prinz, 2001; *simulation theory*: Jeannerod, 2001). Dating back to the original idea of a bidirectional link between an action and its effects (i.e., *ideomotor theory*: Herbart, 1825; James, 1890; for an overview, see Koch, Keller, & Prinz, 2004; Shin, Proctor, & Capaldi, 2010), perceptual-cognitive approaches emphasize the role that the effects of an action have during the selection, planning, and execution of an action. The basic idea of perceptual-cognitive approaches is that motor actions are guided by way of representations holding information about the perceptual effects of motor actions. In this sense, actions are primarily guided by cognitively represented effects. Specifically, motor actions serve the individual to cause changes within the environment (i.e., perceptual effects), and these perceptual effects, in turn, serve as an essential control variable to guide future motor action. Thus, perceptual-cognitive approaches to motor action assume a close functional relationship between motor action and the corresponding, cognitively represented perceptual effects (e.g., Mechsner, 2004; Nattkemper & Ziessler, 2004). While skilled action is thought to rely on well-developed effect representations, motor learning is a result of the constitution and the development of effect representations. As a motor action is executed, the effects thereof are being perceived by the person, and this information is stored in terms of effect representations. Future motor action, in turn, is then guided and controlled by way of these effect representations. Accordingly, practice leads to more detailed effect representations, which more efficiently guide and control our actions.

Thus, while peripheral or ecological approaches de-emphasize the role of the person in favor of the environment and central or cognitive approaches underestimate the role the environment plays in motor action, perceptual-cognitive approaches acknowledge a major role in motor action to cognition, and, at the same time, put emphasis on the environment in terms of the effects the person causes therein. In this sense, perceptual-cognitive approaches focus both on the bidirectional link between the person and the environment (i.e., ecological component) and on the centrally represented information (i.e., cognitive component) that guides perception and action and their development during motor learning. One such perceptual-cognitive approach, arising in the tradition of Bernstein (1947, 1971, 1996), and being situated at the interface of cognitive psychology and movement science, is the *cognitive action architecture approach* (CAA-A; Schack, 2002, 2010). As the CAA-A is central to the objective of the present work, the essential tenants of this approach are going to be introduced and elaborated upon in more detail in chapter 1.4.

1.2 Mental practice and motor learning

1.2.1 Mental practice and its influence on the motor action system

Among the various types of practice which have been suggested to affect motor performance and to promote learning, physical and mental practice have received the greatest attention, both in basic and applied research, as well as in sports.

While physical practice is concerned with the overt rehearsal of a motor action (i.e., the planning, the execution, and the evaluation of a motor action), and thus with the actual experience, mental practice represents the covert rehearsal of a motor action, and thus the imagined experience with the motor task at hand.

The ability to practice mentally, that is to "perform" an action repeatedly in one's mind, is a powerful means of human beings, and the potential of mental practice to influence the performance and the learning of a motor action has been both fascinating and puzzling to researchers in the field. Mental practice in the sense of motor imagery training (as opposed to other forms of mental practice such as self-talk, for instance; for classification, see e.g., Driskell, Copper, & Moran, 1994; Morris, Spittle, & Watt, 2005) can be understood as the covert rehearsal of a motor action by way of motor imagery, whereas actual or physical practice implies overtly rehearsing a motor action:

> "Imagery, in the context of sport, may be considered as the creation or re-creation of an experience generated from memorial information, involving quasi-sensorial, quasi-perceptual, and quasi-affective characteristics, that is under the volitional control of the imager, and which may occur in the absence of the real stimulus antecedents normally associated with the actual experience." (Morris et al., 2005, p. 19)

Thus, in contrast to perception, imagery relates to the creation or re-creation of a real-world experience, with this process taking place in the absence of the actual sensory stimulus (e.g., Annett, 1995a; Farah, 1984; Morris et al., 2005). To explain, one can "see" an image, "hear" a sound or "feel" a touch in one's mind, although the actual image, sound, or touch is not present at that time. Analogous to imagery in general, motor imagery denotes imagining oneself performing a particular motor action without actually executing it at the same time (e.g., Jeannerod, 1994, 1997; Jeannerod & Decety, 1995; for a discussion on its conceptualization, see Morris et al., 2005), and the repeated use of motor imagery results in what is called mental practice (i.e., motor imagery training).

While physical practice has been acknowledged to be the most effective means to induce motor learning, mental practice and its effect on motor performance has been debated extensively. So far, both physical and mental practice are considered to be effective to some extent in improving performance, and, more importantly, in promoting the learning of a motor action (e.g., Corbin, 1967a, 1967b; for reviews and meta-analyses, see Driskell et al., 1994; Feltz & Landers, 1983; Feltz, Landers, & Becker, 1988; Grouios, 1992; Hinshaw, 1991; Richardson, 1967a, 1967b). Meta-analyses on the effectiveness of mental practice have investigated the magnitude of effect that mental practice in comparison to physical practice has on the performance of a motor action (e.g., Driskell et al., 1994; Feltz & Landers, 1983; Feltz et al., 1988). For instance, Driskell et al. (1994) conducted a meta-analysis on the effects of mental practice in comparison to irrelevant practice and physical practice. The authors reported small to moderate effect sizes from their analysis of 35 studies, with an overall average effect size of d = .53 for mental practice. In contrast, moderate to strong effect sizes were reported for physical practice, with an average of d = .78. From their meta-analysis, the authors concluded that mental practice is not as effective as physical practice, but that it can have a positive effect on performance. Furthermore, combined mental and physical practice has been suggested to be as effective as physical practice or even superior to physical practice only (e.g., McBride & Rothstein, 1979). In general, mental practice is considered a potentially effective means to improve performance and to promote learning. Thereby, the main factors influencing the effectiveness of mental practice are imagery ability (e.g., Goss, Hall, Buckolz, & Fishburne, 1986; Guillot & Collet, 2005; for a review, see McAvinue & Robertson, 2009), imagery perspective (e.g., Epstein, 1980; White & Hardy, 1995; for a review, see Morris & Spittle, 2012), imagery modality (e.g., Féry, 2003; for an overview, see Lacey & Lawson, 2013), type of task (e.g., McBride & Rothstein, 1979; Ryan & Simons, 1983; for a meta-analysis, see Driskell et al., 1994), and level of expertise (e.g., Corbin, 1967b; for a meta-analysis, see Driskell et al., 1994; for an overview on factors that influence the effect of mental practice, see Morris et al., 2005; Schuster et al., 2011).

1.2.2 Theoretical perspectives on mental practice

In attempting to answer the question why mental practice influences the motor action system and what the underlying mechanisms are, researchers have provided a variety of possible explanations, of which the *psychoneuromuscular theory* (Jacobson, 1931), the *symbolic learning theory* (Sackett, 1934), and the *simulation theory* (Jeannerod, 1995, 2001) have been the most prominent ones (for an overview, see e.g., Heuer, 1985; Morris et al., 2005; Murphy, 1990; Murphy, Nordin, & Cumming, 2008; Schack, 2006). In the following, both traditional as well as recent approaches are presented, thereby maintaining the distinction between central, peripheral, and perceptual-cognitive perspectives as has been introduced previously for motor learning (see chapter 1.1). Whereas peripheral hypotheses spotlight peripheral processes during motor imagery (e.g., within the person such as muscular activity or between person and environment such as affordances, see chapter 1.2.2.2), central hypotheses emphasize the central processes during motor imagery (e.g., neural correlates and symbolic representations within the person, see chapter 1.2.2.1).

1.2.2.1 Central perspective on mental practice

Central hypotheses of mental practice have in common the assumption of some form of representation. Information processed during motor imagery is thought to be stored in a representational format (for details on the *imagery debate*, see e.g., Kosslyn, Thompson, & Ganis, 2010; Pylyshyn, 2003), and accessed and retrieved again while imagining. This imagery process incorporates the generation of an image by way of the retrieval from long-term memory as well as the maintenance and transformation of an image in working memory (for more details on the specific processes, see Farah, 1984; Munzert, 2001; Munzert & Zentgraf, 2009).

One of the early, centrally focused explanations for mental practice was the *cognitive hypothesis* emerging from the field of cognitive psychology (cf. *symbolic learning theory*; Sackett, 1934). According to this hypothesis, the sequence of a movement is coded by way of symbols, and thus imagery helps to code a movement sequence symbolically. Specifically, the repeated imagining of a movement sequence is suggested to aid the encoding of the symbolic components of the sequences (e.g., the sequence of sub-movements of the golf putt). Thus, mental practice is suggested to improve motor performance through the repetition of symbolic components of the movement sequence during imagery, thereby resulting in a better symbolic representation that, in turn, facilitates subsequent motor performance. The symbolic learning theory has clearly proven valuable as it stimulated groundwork research on the cognitive-motor hypothesis (for more details, see chapter 3.4). Nowadays, however, the cognitive hypothesis is regarded insufficient, as it cannot explain the effects of mental practice on tasks with little cognitive demands such as strength tasks (e.g., Yue & Cole, 1992; Reiser, Büsch, & Munzert, 2011).

To account for this, the *programming hypothesis*, tracing back to Schmidt's *schema theory* (Schmidt, 1975), has been proposed more recently (Heuer, 1985). This hypothesis suggests that the central processes (i.e., the motor programming) associated with the peripheral concomitants of motor imagery (i.e., the neuromuscular activation) are responsible for the mental practice effects. Mental practice is effective because it induces internal feedback which, in turn, causes corrections of the motor programming. Specifically, the efferent commands for muscle activation are specified during motor imagery similar to motor execution, but do not take full effect in terms of actual muscle activation and resulting movement. In this sense, internal knowledge of result is available during motor imagery and allows for corrections of the motor program. This internal feedback serves to refine the motor program and to improve the programming of the motor action. In sum, mental practice according to the programming hypothesis serves to activate and to refine a motor program by way of internal feedback. Evidence in favor of the basic assumptions of this hypothesis comes mainly from the neuroscientific perspective on mental practice (for a review, see e.g., Guillot & Collet, 2010).

1.2.2.2 Peripheral perspective on mental practice

A direct opponent of the early cognitive hypothesis was the *ideomotor hypothesis*[2] (cf. the *psychoneuromuscular theory*; Jacobson, 1931), stemming from the field of psychophysiology. Originating from what is known as the *carpenter effect* (Carpenter, 1894), the psychoneuromuscular theory focuses on the activation of muscles, and thus more peripheral processes, during imagery. Specifically, the psychoneuromuscular theory states that muscular activity occurs in body parts involved (e.g., flexors of the upper arm) in the movement that is being imagined (e.g., bending the arm). Although being not as strong as during the execution of a movement, the muscular activity is suggested to be identical in its activation pattern during covert imagery to that during overt execution, thereby leading to neuromuscular feedback. Accordingly, mental practice is suggested to improve motor performance in the way that a similar pattern of muscles like the one during movement execution is activated during imagery. This is thought to allow for adjustments within the motor action system via neuromuscular feedback, leading to changes in subsequent movement execution, and thus resulting in motor learning. However, as neuromuscular feedback during the execution and the imagery of a motor action differs severely, and since mental practice effects have been found in studies controlling for and preventing muscular activity during imagery (e.g., Lutz, 2003; Yue & Cole, 1992), the ideomotor hypothesis does not hold as an explanation (e.g., Heuer, 1985; Mulder, deVries, & Zijlstra, 2005; Munzert, Reiser, & Zentgraf, 2014). While this hypothesis has taken a backseat in recent years as an explanation for mental practice, the role of muscle activation during imagery is still highly debated (e.g., Guillot, Di Rienzo, MacIntyre, Moran, & Collet, 2012; Lutz, 2003; for an overview, see Guillot, Lebon, & Collet, 2010).

More recently, mental practice has been approached from an ecological perspective, proposing the *ecological hypothesis* as a possible explanation (cf. *action-based imagery*; Boschker, 2001; Boschker, Bakker, & Michaels, 2002). This

[2] The term *ideomotor hypothesis* has been introduced by Heuer (1985), and must not be confused with the ideomotor theory (James, 1890) and the perceptual-cognitive perspective on mental practice (for details, see next chapter)

hypothesis is rooted in the theory of direct perception, and the basic idea of a reciprocal relation between the person and the environment (Gibson, 1977, 1979), and thus focuses on the person-environment relation in general, and the affordances an environment offers in particular. Specifically, the possibilities to act offered by the environment and the subsequent realization of a possibility during motor action are being imagined during motor imagery. That is, motor imagery is concerned with imagining affordances and their realization. Accordingly, mental practice is thought to induce motor learning by way of mentally rehearsing the relation between affordances and their realization, leading to changes within the motor action system, and thus motor learning. Importantly, according to the ecological hypothesis, so-called action-evoked information (i.e., perceptual effects) is lacking during the imagination of a motor action, and as such reflects the main difference between mental and physical practice (Boschker et al., 2002). This hypothesis delivers a new and interesting perspective within the theoretical debate of basic mechanisms that underlie mental practice. Importantly, however, although the focus on affordances and their realization widens the view on mental practice and its effects, it remains unclear from this hypothesis how the creation of an image shall take place without considering a memory that stores the information and, accordingly, a representation that allows for the re-creation of an image.

1.2.2.3 Perceptual-cognitive perspective on mental practice

Arising from the neuroscientific perspective on motor imagery and mental practice, and originating from the principle of *functional equivalence* (Finke, 1979; Jeannerod, 1994, 1995; Johnson, 1980), the *simulation hypothesis* has attracted many researchers' attention (cf. *simulation theory*; Jeannerod, 2001, 2006). According to the principle of functional equivalence, the imagery and the execution of a motor action are considered functionally equivalent. Specifically, both are suggested to adhere to the same principles such as temporal regularities as well as neural processes and structures involved in both imagined and actual action (e.g., Decety, 1996, 2002; Grèzes & Decety, 2001; Jeannerod & Frak, 1999). As a continuation of this principle, Jeannerod proposed the *simulation theory* of action as a framework for motor cognition

(Jeannerod, 2001, 2006). According to simulation theory, actual and simulated (e.g., imagined or observed) actions are all actions, as each involves a covert stage of action (i.e., *simulation stage*; *s-stage*). In other words, actual actions imply a covert and an overt stage of action, while simulated actions imply a covert stage of action. To this extent, all of these different types of s-states to some degree involve the activation of the motor action system. Along these lines, mental practice is suggested to be effective as it is functionally equivalent to physical practice, activating and inducing changes within the motor action system.

This theory clearly provides an overarching framework to investigate properties that are functionally equivalent across overt and covert stages of action, such as the imagery and the execution of an action. As such, the simulation hypothesis delivers an explanation for mental practice suggesting that mental practice can be effective to the degree that there is a functional equivalence in both stages of action. Up to now, the simulation hypothesis is considered the most integrative approach to mental practice effects (e.g., Murphy et al., 2008).

More recently, originating from a perceptual-cognitive approach to motor action (i.e., the *cognitive action architecture approach*; CAA-A), the *perceptual-cognitive hypothesis* has been proposed (Schack, 2002, 2004, 2006). Following a general introduction to the CAA-A in chapter 1.4, this hypothesis is introduced in more detail in chapter 1.4.4. Beforehand, empirical approaches to motor learning and mental practice as well as the current state of research addressing the functional role of mental representation in particular are going to be described in the following chapter.

1.3 Mental representation, motor learning and mental practice

1.3.1 Empirical approaches to motor learning and mental practice

Up to now, the phenomenon of motor learning as induced by (mental or physical) practice has been approximated by a variety of empirical approaches (e.g., Seidler & Meehan, 2013). After introducing and discussing in short the two most commonly used indicators of motor learning, namely changes in motor performance and changes in brain activation (i.e., behavioral and neural changes[3]), research directly addressing the role of mental representations (i.e., cognitive changes) is summarized in the next few chapters.

Traditionally, motor learning as induced by physical practice has been operationalized as changes in motor performance (i.e., behavioral changes). Specifically, as learning itself cannot be observed, researchers have agreed on persisting changes in motor performance to be a valid indicator of motor learning (e.g., Schmidt & Lee, 2011). Accordingly, in cases that (a) changes in motor performance occur and persist over time (i.e., retention) or that (b) changes in motor performance of a particular task lead to changes on a related task (i.e., transfer), it is concluded that motor learning has taken place (for details on the performance-learning distinction, see e.g., Kantak & Winstein, 2012). Interestingly, it is assumed that underlying representations have developed to some extent together with improvements in motor performance. To put it differently, conclusions about motor learning that are inferred from motor performance inherit the assumption that representation and performance directly relate to one another. To give an example, based on schema theory (Schmidt, 1975), research on the variability of practice has measured the degree of learning by way of changes in motor performance both directly after acquisition phase and after a retention interval (e.g., Shea & Kohl, 1990). Based thereon, conclusions have been drawn with respect to underlying representations of the motor action. Specifically, if practice leads to better retention performance, and thus in this sense greater learning, then it is suggested that varied practice leads as well to better developed representations compared to specific practice.

More recently, the adaptation of the brain (i.e., neural changes) as a result of motor learning has received a great deal of attention as an indicator of motor learning (e.g., Wadden, Borich, & Boyd, 2012). From a neuroscientific view, motor learning has been approached by way of changes in the brain, both in its anatomy and its physiology. From this, insights into central changes within the motor action system

[3] For the sake of convenience, both changes in overt motor performance and changes in covert brain activation will be referred to as behavioral and neural changes in the following.

have been provided, and conclusions have been drawn regarding the neural aspects of motor control and learning, and the neural plasticity of the brain respectively (for a recent meta-analysis, see Hardwick, Rottschy, Miall, & Eickhoff, 2013; for reviews, see also e.g., Dayan & Cohen, 2011; Doyon & Benali, 2005; Doyon & Ungerleider, 2002; Halsband & Lange, 2006; Kelly & Garavan, 2005; Ungerleider, Doyon, & Karni, 2002). Interestingly, by employing a neuroscientific approach to motor learning, conclusions about the representation of a motor action are being inferred from neural parameters. For instance, Doyon et al. (2009) reviewed research on dynamic changes taking place within the cortico-striatal system and the cerebellum during motor learning. From this, the authors drew conclusions about representations such that the anterior part of the putamen is critical for spatial representation development, while the posterior part of the putamen is critical for motor representation development. Hence, from the involvement of particular brain areas during motor learning and thus their role within the learning process, conclusions are drawn with respect to the representation of motor action.

Similar to motor learning by physical practice, researchers investigating the influence of mental practice on the motor action system traditionally have focused on behavioral changes as a variable to measure the degree of learning. That is, the effectiveness of mental practice in comparison to physical practice, or the combination of both in comparison to physical practice only, has been investigated with regard to the motor performance of an action (e.g., Driskell et al., 1994). In more recent years, motor imagery and mental practice have been approached as well from a neurophysiological perspective, thereby investigating the adaptations within the human brain. Specifically, neurophysiological correlates of both actual and imagined actions have been examined, and conclusions regarding the functional equivalence of real and simulated actions have been drawn (e.g., Grèzes & Decety, 2001; for an overview, see Decety, 2002). Particularly, in the realm of simulation theory (Jeannerod, 2001, 2006), the study of action representation from a neurophysiological point of view has received tremendous research interest (e.g., Guillot, Di Rienzo, & Collet, 2014). More recently, researchers started to examine the effects of mental practice on brain activation, both in comparison to no practice, and to physical practice (e.g., Allami et al., 2014; Jackson, Lafleur, Malouin, Richards, & Doyon, 2003; Pascual-Leone, Dang, Cohen, Brasil-Neto, Cammarota, & Hallett, 1995; Zhang, Long, Ge, Xu, Jin, Yao, & Liu, 2014; Zhang, Xu, Zhang, Hui, Long, Zhao, & Yao, 2012). From this, conclusions about the representation of a motor action and its development are drawn. For instance, Zhang et al. (2014) recently investigated changes in functional connectivity in resting state as a result of mental practice. The authors found alterations in cognitive and sensory resting state networks in various brain systems after learning by way of motor imagery (i.e., mental practice), while no alterations in connectivity were found in the control condition (i.e., no practice). From this, the authors concluded that modulation of resting-state functional connectivity as induced by mental practice may be associated with functional reorganization in the brain. Moreover, the authors stated that “these alterations in resting-state functional connectivity after learning potentially subserved the establishment of motor schema (…)” (Zhang et al., 2014, p. 4). Thus, from changes in particular brain areas as a result of mental practice, it is concluded that the representation of motor action has changed.

Although both behavioral and neural changes have proven to be valuable indicators of motor learning as induced by mental or physical practice, they do not cover the whole phenomenon and bear several limitations (e.g., Rose & Christina, 2006). Most importantly, employing behavioral or neural changes as an indicator of motor learning, thereby drawing conclusions about underlying representations of action, inherits the assumption of an isomorphic relationship between the indicator and mental representation development. Specifically, if the indicator of motor learning (here: motor performance or brain activation) changes, the underlying representation is suggested to do so as well, and to the same degree. However, this kind of logic poses several problems and limits the study of motor learning and the conclusions drawn from findings in the field. For instance, in case of obvious performance changes, performance is not entirely determined by permanent factors such as level of skill, but also by temporal factors such as motivation. Therefore, changes in performance do not necessarily represent learning, and mental representation development respectively.

Conversely, in case of the lack of performance changes, learning may have taken place such that the representation may have changed, but it may not have resulted in observable changes in performance, and thus does not become evident on the performance level that is being measured. Furthermore, although the neuroscientific approach to motor learning is essential in contributing to our understanding of central processes taking place in the brain during motor learning, neural changes do not necessarily allow for conclusions regarding the cognitive adaptations within the motor action system. Specifically, from findings elucidating neural changes associated with motor learning as induced by mental and physical practice, it is not clear what these neural changes stand for on a cognitive representational level. As such, they do not allow for specific conclusions regarding the cognitive representation of a particular motor action in long-term memory and its development over the course of learning. Given these limitations it seems crucial to go beyond either behavioral or neural changes and to highlight the role of mental representation itself, if the aim is to thoroughly understand the complexity of the adapting motor action system during learning.

Taken together, as for motor learning in general and mental practice in particular, both behavioral and neural variables have mainly been employed to measure the degree of learning within the motor action system, and to draw conclusions with respect to underlying representations of an action (e.g., Hodges & Williams, 2012; Rose & Christina, 2006). Learning thus has usually been inferred from and empirically approached by either changes in motor performance or changes in the brain. At the same time, conclusions about underlying representations are drawn based on these changes, inheriting the assumption of an isomorphic relationship between both. If representations are considered the basis of action organization, however, approaching the mental representation itself in the organization and during the learning of motor action is a more precise indicator of motor learning. Accordingly, having a closer look at the functional role of representations may shed further light on the learning processes inherent in the adapting motor action system during motor learning as induced by mental and physical practice. An overview of research lines directly addressing the functional role of representation in motor control and learning will therefore be given in the following.

1.3.2 Evidence on mental representation of complex action across skill levels

Research addressing questions relating to the functional role of mental representation in motor action, has mainly been conducted in the field of expertise, thereby drawing comparisons across skill levels (for overviews, see Hodges, Huys, & Starkes, 2007; Schack, 2010). For instance, Allard and Burnett (1985) found basketball experts to classify problems according to functional principles, while novices did so adhering not to functional, but to superficial features. Specifically, expert players classified pictures representing various aspects of the game into distinct and discriminating meaningful categories (e.g., offensive and defensive fundamentals), whereas novices classified pictures by way of obvious characteristics such as number of players (e.g., individual and team). Moreover, French and Thomas (1987) were among the first to show that skill-related knowledge differs according to skill level. Specifically, expert basketball players differed not only in their superior performance (e.g., shooting skill) from their novice counterparts, but also in their basketball-specific knowledge (e.g., position of the players). In addressing differences in problem representations between elite and non-elite athletes, Huber (1997) found that more features defined the central concepts of elite athletes, and the interrelations between the concepts were more numerous compared to non-elite athletes. Furthermore, the organization of movement related knowledge has been systematically investigated addressing problem representations and *condition-action-goal linkages* across skill levels by McPherson and colleagues analyzing verbal reports. From this research, experts' problem representations differed from those of novices. For instance, the authors reported more elaborate conceptual networks of declarative and procedural knowledge (i.e., condition-action-goal linkages), regarding both skills and tactics (e.g., McPherson, 1993; for an overview, see McPherson & Vickers, 2004; French & McPherson, 2004).

In the realm of the cognitive action architecture approach (for details, see chapter 1.4), Schack and Mechsner (2006) investigated the *structuring and dimensioning of mental representations* across skill levels, employing the structural dimensional analysis of mental representations (SDA-M) as an experimental approach to mental representations of complex action that does not depend on individuals' explicit statements. The authors examined representational networks of the tennis serve in experts and non-experts, eliciting distinct differences in mental representations across skill levels. Specifically, skilled individuals held functionally structured representations of the tennis serve (i.e., reflecting well the three movement phases pre-activation, strike, and final swing), whereas unskilled individuals did not have such structured representations available. Such differences in mental representations across skill level have been shown to generalize to various motor skills in a variety of sports such as dance (e.g., Bläsing, 2010; Bläsing, Tenenbaum, & Schack, 2009), volleyball (e.g., Velentzas, Heinen, Tenenbaum, & Schack, 2010), judo (e.g., Weigelt, Ahlmeyer, Lex, & Schack, 2011), and windsurfing (e.g., Schack & Hackfort, 2007), and have as well been reported in the area of manual action (e.g., Braun et al., 2007; Stöckel, Hughes, & Schack, 2012).

Accordingly, the results of research investigating the structure of mental representation of complex action can be condensed into three main findings: (1) the mental representation of skilled individuals can be characterized by a distinct structure, with the representation reflecting a particular formation of basic action concepts, (2) the structure of a skilled individual's mental representation is functional in the sense that the formation of basic action concepts corresponds to the biomechanical and functional task demands, and (3) mental representation structures are similar across skilled individuals. Instead, mental representation structures of unskilled individuals differ remarkably, and their representations do not hold a distinct, functional structure. From this and other research, skilled action in comparison to unskilled action is thought to be based on well-developed representations, thereby assisting to control the motor action system during action execution. In this sense, elaborate representations allow for refined movement execution, resulting in appropriate actions and thus stable performance in a given situation.

1.3.3 Evidence on mental representation of complex action and motor learning

While much attention has been directed towards differences between skilled and non-skilled individuals in both their observable performance and their underlying representations, less research has addressed questions relating to mental representation development and the functional role of mental representations during motor learning.

Körndle and colleagues (Körndle, 1983a, 1983b; Zimmer & Körndle, 1988) were among the first to show that cognitive units of action-related knowledge evolve during motor learning and are being integrated into hierarchies during this process. For instance, Körndle (1983a) compared individuals learning quickly (i.e., fast learners) to those learning slowly (i.e., slow learners) and showed that fast learners differed from slow learners during the learning process, both in their pedaling performance (i.e., as measured by way of effective forces and velocity) as well as in their representations (i.e., as measured by way of feature-ratings and interviews). Specifically, fast learning individuals were able to give precise statements (e.g., keep upper body still; place whole feet on footboard), while slow learning individuals gave no more than global statements (e.g., keep balance; go rapidly) on the learning process after practice, indicating different degrees of hierarchy in their representation structures. Continuing this work, Lippens (1992, 2001) examined *subjective theories* during motor learning. Subjective theories as cognitions of the self and the world during rowing were investigated by way of a sorting task (for details on the task, see Lippens, 2001). From this work, Lippens (1992) reported distinct differences between fast and slow learning individuals. Specifically, fast learning individuals were better able to identify relevant knowledge (e.g., sound of oar blade and water) and to quickly and more efficiently access their knowledge. Instead, slow learning individuals spent more time on their knowledge search, and used more numerous terms in their descriptions, thereby getting lost in details more often. From this, the authors concluded that representations of rowing become hierarchically integrated during learning. Similarly, Seiler (1995;

1997) researched the nature and change of *representational frames* during motor learning, thereby supporting the idea of hierarchical structuring of representations during motor learning (for related work, see also e.g., Blaser, Stucker, Körndle, & Narciss, 2000; Kromer, 2007; Wiemeyer, 2001).

Overall, compared to research addressing differences in experts' and novices' representations of complex action, relatively little research has been conducted that investigates the functional role of representations during motor learning (for an overview, see Schack, 2003; for a discussion, see Lippens, 2009). From research directly testing for changes in underlying representations of complex motor action during learning, action-related knowledge has been shown to change over the course of learning such that representations of complex action adapt and become hierarchically structured.

1.3.4 Evidence on mental representation of complex action and mental practice

While some research has been directed toward the functional role of mental representations during motor learning as induced by physical practice, research on the functional role of mental representations during motor learning as induced by mental practice is scarce.

A first step in direction of considering the influence of mental practice on both the (covert) level of representation and the (overt) level of performance was taken by Narciss and colleagues (Narciss, 1993, 1996, 2001; Narciss, Reischle, & Eberspächer, 1994). Narciss (1993) examined the change of internal representations and biomechanical characteristics of the breaststroke in swimming over the course of practice. In their study, one group of students practiced physically, while another group of students practiced mentally in addition to physical practice. The authors found that both groups improved their breaststroke performance over time. Interestingly, the combined mental and physical practice group revealed a more developed internal representation in comparison to the physical practice only group after practice. Narciss (1993, 2001) did not further discuss this somewhat unexpected finding, but concluded that it may prove fruitful to consider both the covert level of representation and the overt level of performance in future studies. Although the study reflects seminal work on the influence of mental practice on the mental representation of a complex action, the effects of mental and physical practice have not been investigated systematically within this study. However, if one aims to thoroughly understand the motor action system, and to approach motor learning as well as mental practice from within, it is essential to isolate the distinct contributions of each practice type to each level of the adapting motor action system.

Taken together, to our knowledge, there is only one study that directly addresses the functional role of mental representation during motor learning as induced by mental practice[4]. Apart from this work, evidence on the influence of mental practice on mental representation development, especially in comparison to physical and no practice, is lacking. The work at hand aims at systematically investigating the influence of mental and physical practice on the motor action system with a particular focus on the perceptual-cognitive level of action organization and the functional role of mental representation (for details, see chapter 1.5). Therefore, the cognitive action architecture approach is going to be introduced in the following.

1.4 The cognitive action architecture approach to motor learning

1.4.1 Hierarchical organization of actions

Central to the *cognitive action architecture approach* (CAA-A; Schack, 2002, 2004, 2010) is the idea of a hierarchical organization of motor action. According to this perceptual-cognitive approach, motor actions are organized in a stratified manner, with two main systems (i.e., the *mental system* and the *sensorimotor system*) contributing to the construction of motor action (see also Table 1.1). Each of the two systems encompasses two levels of action organization. Specifically, from the higher to the lower levels in the hierarchy, the mental system is comprised of the *level of mental control* (i.e., level IV) and the *level of mental representation* (i.e., level III), and the sensorimotor system is composed of the *level of sensorimotor representation* (i.e.,

[4] For details on mental training based on mental representation (MTMR), see chapter 5.3

level II) and the *level of sensorimotor control* (i.e., level I). Thus, the motor action system is thought to operate on four different levels: two levels with regulatory functions (i.e., the level of mental control and the level of sensorimotor control) serving as control entities, and two levels with representational functions (i.e., the level of mental representation and the level of sensorimotor representation) serving as reference entities. While the sensorimotor system, being the "sub"-part (i.e., the lower part) of both systems within the hierarchy, is concerned with the direct transformation of intentions into actions, i.e., the transformation of the intent to move into actual movement [*direkte Absichtsrealisierung*], the mental system, being the "super"-part (i.e., the higher part) within the hierarchy, is concerned with the indirect transformation, i.e., the transformation of the intent to move into real movement is mediated via plans, strategies etc. [*indirekte Absichtsrealisierung*] (cf. Goschke, 1996). When a motor action is being performed, all four levels of the system are involved, with each level contributing in its specific manner.

Table 1.1

Levels of action organization according to the cognitive action architecture approach

Code	**Level**	**Main function**	**Subfunction**	**Means**
IV	Mental control	Regulation	Volitional initiation; Control strategies	Symbols; Strategies
III	Mental representation	Representation	Effect-oriented adjustment	Basic action concepts
II	Sensorimotor representation	Representation	Spatial-temporal adjustment	Perceptual effect representations
I	Sensorimotor control	Regulation	Automatization	Functional systems; Basic reflexes

Note: This table is adapted from Schack, 2004, p. 408.

According to Schack (2002, 2010), the level of mental control is primarily concerned with the voluntary control of action. On this level, the action goal is set and the intended action effect is coded via symbols and strategies. The level of mental representation serves as a cognitive reference system for subsequent action control, mediated via basic action concepts. Specifically, on this level, the intended effect is transferred into a model of the motor action to be executed, by delivering reference values for action execution. On the level of sensorimotor representation, modality-specific afferent and re-afferent information is represented, thereby delineating the corresponding effects of the action. Accordingly, this level is mediated by way of perceptual information. Finally, the level of sensorimotor control is concerned with action execution, and as such it directly relates to the environment. Action control on this level operates by way of synthesis of afferent information ([*Afferenzsynthese*]; cf. Anochin, 1967) and the comparison of actual effects to the intended effects, resulting in adequate executive commands for control purposes, and thus action (for an overview of the CAA-A, see also Schack, 2004; Schack, Bläsing, Hughes, Flash, & Schilling, 2014).

To illustrate, in the case of golf putting, the goal to sink the ball is established by the golfer on the level of mental control. Moreover, a strategy is laid out how this goal is going to be achieved (e.g., the breaks, the speed of the green and many other factors are considered during the process of setting the target line for a particular putt). The golfers' mental representation of the putt serves to transfer the action goal into a model of the putting movement to be executed in order to perform a successful putt. Modality-specific information of the putt (e.g., the feel of grip pressure during the swing or the sound of the impact when the club hits the ball) is available from the level of sensorimotor representation. Sensorimotor control during the putt itself is then guaranteed by comparing the actual effects (e.g., the actual speed of the downswing) to the intended effect (e.g., the intended speed of the downswing), and by correcting the putting movement accordingly (e.g., reducing the acceleration of the club during downswing).

As described above, the realization of a movement necessitates the involvement of each level and the interaction of the four levels. Likewise, each level fulfills distinct functions. Of particular importance within the CAA-A is the role that mental representations play within the organization of actions, and thus in motor control and motor learning. Therefore and for the specific purpose of the present work, the construct of mental representations within the CAA-A is described in more detail.

1.4.2 Mental representation and the organization of actions

According to the CAA-A, the organization of an action, and thus the controllability of the motor action system, is thought to be closely tied to representational networks of action concepts (i.e., mental representations). Well-developed mental representations form the basis of well-organized actions and as such ensure that actions can be controlled within the motor action system (e.g., Bläsing, 2010; Schack & Mechsner, 2006; see also chapter 1.3.2). Analogous to the idea that objects are being represented by way of object concepts in long-term memory (e.g., Ach, 1921; Hoffmann, 1986, 1993; Rosch, 1978), actions are thought to be represented by way of action concepts (Schack, 2002, 2010). *Basic action concepts* (i.e., BACs) represent cognitive compilations or chunks with regard to the realization of an action goal. Specifically, these compilations are thought to be comprised of body postures and movement elements together with their sensory consequences. To illustrate, grip check as a BAC of the golf putt is a cognitive chunk serving a particular action goal (i.e., to ensure an optimal grip during the preparation of the putting movement before initiation of the backswing). As such it is comprised of the corresponding body posture (e.g. standing up right, hips slightly flexed, upper body leaning forward, holding the putter in hands) and movement elements (e.g., take grip, move fingers until in right position) together with their sensory consequences (e.g., feel hands touching the surface of club; sense slight pressure in fingers, see both hands touch each other; for examples on the tennis serve, see Schack & Mechsner, 2006).

Accordingly, mental representations of actions are considered representational frameworks comprised of basic action concepts. The *structuring* of the mental representation is defined by the relations between the basic action concepts. The relations between the BACs, in turn, are feature-based. That is, each proximity or distance between the concepts of a given set is determined by corresponding features (i.e., type, number, and relevance of features), both functional and sensory ones that are closely interconnected. While the functional features relate to the action goals (i.e., they are closely linked to level IV), the sensory features relate to the afferent and re-afferent information of sub-components of the action (i.e., they are closely linked to level II). To illustrate, the BAC “accelerate club” pertaining to the forward swing of the putting movement is determined by functional features (e.g., increase velocity, build energy, create force) and sensory features (e.g., feel the rotation of arms and shoulders, sense the pendulum motion of the club, see the club moving into one’s field of vision). This feature-binding is referred to as the *dimensioning* of the mental representation (Schack, 2002, 2010).

Methodologically, the *structural dimensional analysis of mental representations* (SDA-M) has been developed as a means to measure the distance and the grouping of BACs (i.e., the structuring) as well as the binding of features to BACs (i.e., the dimensioning) within the representation of a complex action (Schack, 2002, 2010; for details, see Schack, 2012). Whereas traditional methods such as interviews and questionnaires require explicit statements from the interviewee (for a methodological overview, see Hodges et al., 2007), the SDA-M approaches representational frameworks from an experimental approach, thereby grasping more implicit knowledge than that gained from the measurement of explicit statements (e.g., Schack, 2012; Schack, 2010; for a discussion, see Kromer, 2007; Kromer & Schack, 2002; Lippens, 2009).

1.4.3 Motor learning and the modification of mental representation

According to the CAA-A, the level of mental representation is of particular importance during motor learning. Whereas the organization of skilled motor action is suggested to be based on a well-developed mental representation, no such well-developed representation is available during the organization of a motor action that is new to an individual. Instead, representations develop during the learning process. In other words, for intelligent and thus stable motor action, a cognitive reference on the level of mental representation is essential. However, such a cognitive reference is lacking in the beginning of the learning process, being no more (if at all) than a simple, unrefined version of a reference estimated based on prior experience with a similar motor action. During the process of motor learning, this cognitive reference is thought to develop from a simple and general representation to a more elaborate and refined version:

> "Within this system, learning could be a product of modifying the mediating conceptual (BAC) structures. These modifications would then impact the total system, so that new constellations are also generated between a level of mental and a level of sensorimotor control through the integration or rearrangement of sensorimotor representation units (perceptual effect-codes). This enables the system to perform an effect-related optimization of relations between intentions and elementary operations depending on the starting conditions." (Schack, 2004, p. 413)

Motor learning, according to the CAA-A (Schack, 2002, 2003, 2004, 2010), reflects an adaptation on the level of mental representation such that the relations and the groupings of action concepts (i.e., mental representation structure) are modified over the course of the learning process (for more details, see chapter 1.5.1).

1.4.4 Mental practice and the modification of mental representation

According to the CAA-A, and the *perceptual-cognitive hypothesis* respectively, mental practice serves to stabilize representational networks of complex action (Schack, 2004, 2006). Specifically, mental practice serves to tie the mental and the sensorimotor representation of a motor action more closely together by simulating a motor action and its effects:

> "Our findings on the cognitive architecture of complex movement (…) open up a new explanation for the effects of mental training: the perceptual-cognitive hypothesis. This posits a representation system in which more strongly cognitive representation units (nodes) are linked to perceptual representations (e.g., kinesthetic-, optical-, or acoustic-effect codes)" (Schack, 2004, p. 429)

According to the perceptual-cognitive hypothesis, mental practice activates and stabilizes the perceptual-cognitive representational networks of complex motor action. Thus, similarly to the central hypotheses, the perceptual-cognitive hypothesis ascribes mental practice effects to the refinement of internal representations. However, according to the perceptual-cognitive hypothesis, mental practice serves to stabilize a representation system of perceptual effect representations allowing for a direct, architecture-based translation of intention into movement (as opposed to the idea of additional representations such as motor programs specifying muscle commands; cf. Heuer, 1985; for a detailed discussion, see Schack, 2002, 2010). That is, the perceptual-cognitive hypothesis differs from the programming hypothesis such that mental practice effects are not based on the refinement of motor programs and thus refined muscle commands, but on the refinement of effect representations and their structures in long-term memory.

The perceptual-cognitive hypothesis opens up an alternative perspective on mental practice. While both peripheral and cognitive accounts of mental practice hold distinct views on the question how mental practice works and by this very fact explain mental practice effects either “from the outside” or “from the inside”, the perceptual-cognitive hypothesis entails both central and peripheral aspects by its focus on effect representations, that is by emphasizing the cognitively represented perceptual effects of the action. As such, a perceptual-cognitive approach may shed further light on mental practice and on how it affects the motor action system, holding an integrative view and taking into consideration different levels of action organization and various opportunities of communication and interaction between them (for more details, see chapter 1.5.1).

1.5 Purpose of the present work

1.5.1 Mental representation and its development with mental and physical practice

As has been described above in more detail, research directly addressing mental representations of complex actions has mainly been conducted in the field of expertise, thereby comparing representations across skill levels (see chapter 1.3.2). By contrast, remarkably little longitudinal research exists on the development of representations over the course of learning. While the influence of physical practice on mental representation development has at least received some research attention (see chapter 1.3.3), research systematically investigating the change and the development of mental representation as a result of mental practice, both in comparison to physical and no practice, is lacking (see chapter 1.3.4). Research has yet to systematically investigate and compare the influence of mental and physical practice on mental representation of complex action.

To systematically examine mental representation development may prove valuable in advancing our understanding of the adapting motor action system. If representations are considered the basis of action organization, it is pivotal to focus on the functional role of representations during motor control and learning. Such a perceptual-cognitive, representation-based perspective seems promising both for motor learning in general and mental practice in particular, as it goes beyond traditional, indirect approaches, and directly addresses the basis of action organization, namely the underlying representation of the action. Therefore, a closer look at representational networks of action concepts and their development during early skill acquisition as a result of mental and physical practice may help to further understand the phenomenon of motor learning as well as the similarities and differences of both types of practice regarding their effect on the motor action system. In addition, comparing both mental and physical practice, and potentially shedding further light on the differential effects of both, may help to better understand or at least approach the basic mechanisms of motor imagery and mental practice.

The cognitive action architecture approach (CAA-A; see chapter 1.4) seems an appropriate framework for this endeavor as it allows for a hierarchical view on the motor action system, and the experimental testing of mental representation of complex action. In short, the organization of skilled motor action, according to the CAA-A, is based on a well-developed mental representation which is elaborate both in its dimensioning and in its structuring. Instead, no such elaborate mental representation is available in the case of unskilled motor action, and thus during action organization of a new motor action (see chapter 1.4.2). Motor learning, from this point of view, is considered the change and functional development of representational networks of complex action in long-term memory, and thus reflects the adaptation of the structuring and dimensioning of mental representations (see chapter 1.4.3). Similarly, mental practice effects are thought to be reflected in terms of order formation in memory (see chapter 1.4.4). Thus, according to the CAA-A, both mental and physical practice should result in more elaborate, and functionally developed representational networks of complex action.

However, it is conceivable that mental and physical practice influence the motor action system and the levels of action organization therein in a different way. Although both practice types are suggested to rely on the same action representation (see chapter 1.2.2.3), they may differ in their influence on the development of mental representation. Drawing on elaborations by Schack (2002, 2003, 2004, 2006, 2010) on motor learning and mental practice from the CAA-A point of view (see chapters 1.4.3 and 1.4.4), the present work aims at taking one step further with regard to different types of practice and their influence on the motor action system during motor learning. In the following, the influence of mental and physical practice on the motor action system, and on the perceptual-cognitive level of action organization in particular, will be sketched.

Whereas skilled action organization relies on well-developed representations, with automatized processes taking place primarily within the sensorimotor system (for more details, see Schack, 2002), no representation is available during unskilled motor action. During early stages of skill acquisition (cf. *cognitive stage*: Fitts & Posner, 1967; *Entwicklung der Grobkoordination*: Meinel & Schnabel, 1987), the motor action system is being challenged, with all levels of action organization being in charge (see Figure 1.1). Specifically, according to Schack (2002), the direct interaction of the person with the environment with regard to a particular motor task allows lower sensorimotor patterns and higher conceptual structures to evolve (as indicated by the circles on the right, see Figure 1.1), and as such helps to stabilize the perceptual-cognitive system within the human motor action system during early stages of motor learning.

The particular influence of mental and physical practice on the levels of action organization, however, may be different. It is conceivable that both types of practice differ in the levels they primarily influence within the motor action system, with mental practice primarily operating on the higher levels, and physical practice primarily operating on the lower levels within the motor action system. Specifically, the primary influence of mental practice on the motor action system may be centered between the mental and the sensorimotor representational levels, while the primary influence of physical practice on the system may be centered between the sensorimotor representational and regulatory levels.

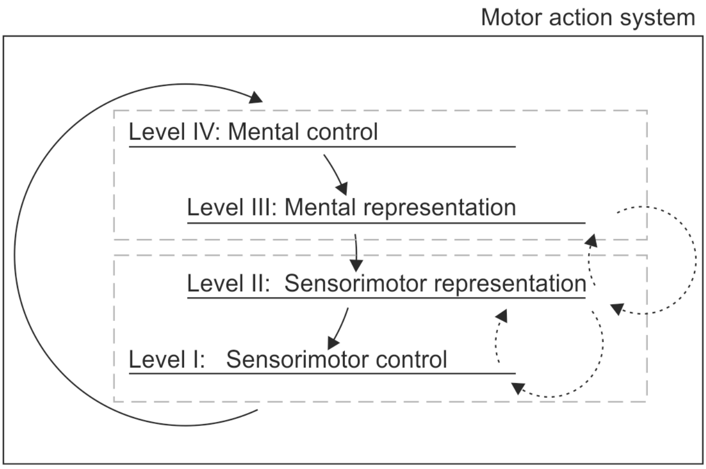


Figure 1.1. The levels of action organization within the motor action system during early stages of motor learning (adapted from Schack, 2002, p. 59).

To explain, physical practice as an "online" type of practice is concerned with the actual experience (for online/offline cf. Beilock & Lyons, 2009) and as such with the integration and storage of sensorimotor information (i.e., feedback) available from actual movement execution. This actual experience may serve to enrich sensorimotor representations, and to refine sensorimotor control (see Fig. 1.1; see also Schack, 2002). Accordingly, physical practice is likely to influence the motor action system mainly by way of the sensorimotor system. These changes within the sensorimotor system might transfer to the mental system, leading to changes on the level of mental representation and on the level of mental control.

In contrast, mental practice as an "offline" type of practice simulates the actual experience, and as such is concerned with a "quasi-experience" and the retrieval and storage of "quasi-sensorimotor information" (i.e., "quasi-feedback") based on the action representation available. This simulated experience may serve to link sensorimotor to mental representations, thereby leading to a refinement of representation structure. Accordingly, mental practice may influence the motor action system mainly through the representational levels at the interface of the mental and the sensorimotor system. These changes on the representational levels of both the mental and the sensorimotor system might transfer to the regulatory levels of both systems, leading to changes on both the mental and the sensorimotor control levels.

Accordingly, from the cognitive action architecture point of view, it is conceivable that mental and physical practice differ in their influence on mental representation of complex action. It may be the case that mental practice influences the level of mental representation within the organization of an action even more so compared to physical practice, as it directly centers around the representational levels and addresses the interface of the mental and the sensorimotor system. Instead, physical practice may influence more so the sensorimotor system, as it centers around the sensorimotor representational and regulatory levels, and as such causes changes on the level of mental representation by way of a refinement of sensorimotor representations.

Thus, while the CAA-A allows for predictions about the role of mental representations within action organization and their development with mental and physical practice, these predictions remain to be empirically tested. So far, mental and physical practice and the development of mental representations of complex action during early phases of motor learning have not been addressed. While research in the realm of the CAA-A, employing the SDA-M, has mainly been conducted using an expert-novice paradigm, thereby comparing mental representation structure across skill levels (between-subject design), no research exists in this area that systematically investigates the change and development in novices' mental representation structure of a complex action during motor learning (within-subject design), thereby examining the influence of both mental and physical practice on mental representation development. In other words, what remains to be examined is the question whether the structure of one's representation of an action changes in a functional way with practice such that the relations of action-related concepts in long-term memory develop in direction of an expert representation. Furthermore, the unique contributions of mental and physical practice, that is both the repeated imagery and the repeated execution of a motor action, to this functional change in mental representation of complex action remain to be explored.

Taken together, research in the field of motor learning, either through mental or physical practice, so far has mainly addressed the behavioral or the neural level, whereas the perceptual-cognitive level of action organization has rarely been looked at. This is somehow surprising as, from a perceptual-cognitive perspective, representations reflect the basis of action organization, and as such the starting and end point of motor learning. If one aims to thoroughly understand the motor action system and its adaptations over the course of learning, one must have a closer look at both the covert and overt levels of a complex action, thereby focusing on the functional role of representations. To learn more about the development of mental representations during motor learning may strongly contribute to a more detailed understanding of the processes taking place within the motor action system during skill acquisition. Accordingly, an integrative understanding of the motor action system may be advanced by shifting the focus toward the level of mental representation of complex action and its role within the organization of action, and by considering learning and the corresponding adaptations as induced by cognitive and motor types of practice (i.e., mental and physical practice) from a representational point of view.

1.5.2 Aims

The overall goal of the present work is to investigate motor learning in general and the relationship between practice and the functional change and development of mental representation of complex action in long-term memory in particular from an architectural, representation-based point of view. Specifically, the influence of two types of practice, mental practice (i.e., covert practice) and physical practice (i.e., overt practice) are considered in the present work. Both types of practice have shown to lead to performance improvements, and thus reflect motor learning. However, motor learning as induced by mental and physical practice has rarely been approached with a specific focus on the perceptual-cognitive adaptations within action organization. To date, research has yet to systematically investigate the influence that mental and physical practice have on the motor action system in terms of the development of mental representation of complex action. The present work aims at bridging this particular research gap.

According to the cognitive action architecture approach (CAA-A; for details, see chapter 1.4), motor learning is regarded from a perceptual-cognitive, hierarchical viewpoint, and as such is based on the functional change and development of action representation in long-term memory. Holding a hierarchical view of action organization, it is possible to investigate the motor action system from different levels of action organization, thereby accounting for similarities and differences in structures and processes between the two types of practice during motor learning (for details, see chapter 1.5.1). Accordingly, the work at hand focuses on exploring the distinct influence of mental and physical practice on mental representation structure of complex action.

In this sense, the present work aims at gaining a deeper understanding of motor learning through the investigation of mental representations of complex action and their development during motor learning. Looking closer at the motor action system in terms of a permanently adapting, complex system may advance a thorough understanding of motor learning and the processes associated with it. In respect thereof, insights into perceptual-cognitive adaptations (i.e., changes in mental representation structure and gaze behavior) that go along with behavioral adaptations (i.e., changes in motor performance) as a result of mental and physical practice will shed further light on the covert processes during motor learning. Furthermore, investigating perceptual-cognitive adaptations together with behavioral adaptations may allow for a deeper understanding of the similarities and differences of covert and overt practice effects onto the motor action system. That is, approaching both mental and physical practice and their (similar or differential) influence upon the motor action system, may widen our understanding of both types of practice, their influence and their limits, and take us a step further in direction of establishing a comprehensive theory of the underlying mechanisms of mental and physical practice.

In short, the main expected outcome of the present work is to gain insights into the perceptual-cognitive adaptations that occur within the motor action system during early skill acquisition as a result of both mental and physical practice. Gaining a detailed understanding, particularly of how mental representations develop during motor learning, will, from a theoretical point of view, shed further light on the covert adaptations that occur with mental and physical practice, and, from an applied point of view, will be the basis for practical work such that basic knowledge can be transferred to the field.

1.5.3 Research questions

The overall purpose of the present work is to examine perceptual-cognitive adaptations within the motor action system as induced by mental and physical practice, with a particular focus on the level of mental representations. To this extent, motor learning is considered as the modification of representational networks of action concepts in memory. Accordingly, the overarching research question is to what extent the mental representation of a complex action changes and develops over the course of learning. Specifically, the structuring of mental representation and its development toward a more elaborate structure with mental and physical practice is being investigated. Along these lines, the present work seeks to answer three main research questions:

1. Does the structure of mental representation change as a result of physical practice and do these changes reflect a development toward a functional structure? Specifically, does the development in mental representation structure differ between practice and no practice during early skill acquisition? (see chapter 2)
2. Does mental representation structure change and develop as a result of mental practice? Specifically, does the development in mental representation structure differ between mental, physical and combined mental and physical practice in early skill acquisition? (see chapter 3)
3. Is the development in mental representation structure as a result of mental and physical practice associated with perceptual changes? Specifically, do mental and physical practice differ in terms of the perceptual-cognitive background of performance changes during early skill acquisition? (see chapter 4)

1.5.4 Predictions

According to the cognitive action architecture approach (CAA-A), the motor action system changes during motor learning, with the two subsystems (i.e., the mental and the sensorimotor system) developing. Specifically, together with performance improvements, motor learning is thought to be associated with functional changes in mental representation of the action. As predicted by the CAA-A, changes in mental representation structure should be evident as a result of practice, and these changes should reflect a development toward a more elaborate structure matching more so with the functional and biomechanical demands of the task. Furthermore, and more specifically, the CAA-A allows for specific predictions about the development of mental representation during motor learning, as induced by mental and physical practice.

Accordingly, it was predicted (a) that physical practice would lead to both improvements in performance and functional changes in mental representation structure toward an expert structure in comparison to no practice (study 1, 2, 3), (b) that mental practice would lead to both performance improvements and a functional development of representation structure toward an expert structure in comparison to no practice (study 2, 3), and (c) that the development in mental representation structure as induced by mental and physical practice would be associated with perceptual changes, that is functional changes in quiet eye duration (study 3). Importantly, we were interested in whether mental and physical practice would have differential effects regarding the perceptual-cognitive adaptations within the motor action system (for details, see chapter 1.5.1; for specific hypotheses of each learning study and further details on the rationales, see chapters 2.1, 3.1, and 4.1).

2 PHYSICAL PRACTICE AND THE DEVELOPMENT OF MENTAL REPRESENTATION STRUCTURE

This chapter is based on the manuscript

Frank, C., Land, W. M., & Schack, T. (2013). Mental representation and learning: The influence of practice on the development of mental representation structure in complex action. *Psychology of Sport and Exercise, 14*, 353-361.

Abstract

Recent research has elicited distinct differences in mental representations between athletes of different skill levels. Such differences suggest that the structure of mental representations changes as a function of skill level. However, research examining how such mental representation structures develop over the course of learning is lacking. In the present study, we examine the effects of practice on the development of one's mental representation of a complex action during early skill acquisition. For this purpose, we created a controllable learning situation, using a repeated-measures design with a control group. More specifically, novice golfers were randomly assigned to either a practice group (n = 12) or a control group (n = 12). Both groups were tested before and after an acquisition phase of three days as well as after a three day retention interval. Mental representation structures of the putt were recorded, employing the structural dimensional analysis of mental representation (SDA-M), which provides psychometric data on the structure and grouping of action concepts in long-term memory. In addition, outcome performance of the practice group was measured, using two-dimensional error scores of the putt. Findings revealed a significant improvement in task performance, as well as functional changes in the structure of the practice group's mental representation. In contrast, no functional adaptations were evident in the mental representation of the control group. Our findings suggest that motor skill acquisition is associated with functional adaptations of action-related knowledge in long-term memory.

2.1 Introduction

During the last 50 years, researchers from cognitive psychology have identified a close relationship between performance and mediating cognitive mechanisms (e.g., Allard & Burnett, 1985; Allard, Graham, & Paarsalu, 1980; Chase & Simon, 1973; Chi & Rees, 1983; French & Thomas, 1987; De Groot, 1965). Along with superior performance, research on expertise has shown that the expert advantage is associated with numerous cognitive adaptations. For instance, experts are better able to recall domain-specific information (e.g., Chase & Simon, 1973), to anticipate future events (e.g., Mowbray & Rhoades, 1959), and to make fast and accurate decisions (e.g., Tenenbaum, 2003). In addition, a long-standing discussion within this field of research has addressed the role of mental representations within the organization of actions. According to this, expert performance has been suggested to rely on well developed mental representations (e.g., Ericsson & Smith, 1991). Specifically, highly-skilled individuals are thought to differ from low-skilled individuals both in their reproducibly superior performance and in their underlying representation of the skill in long-term memory (e.g., Ericsson, 2007).

According to skill acquisition theories, cognitive mechanisms governing task performance develop over the course of learning (e.g., Anderson, 1982, 1993, 1995; Fitts & Posner, 1967; Magill, 2011). To this extent, motor skill acquisition is suggested to be accompanied by changes in the cognitive control structures that mediate the reliance on attention and working memory. More specifically, novice motor performance has been suggested to rely heavily on working memory with movements attended to in a stepwise fashion. In contrast, expert performance is suggested to be supported by integrated task control structures that allow for movements to be automated, thereby placing fewer demands on attention and working memory processes (for an overview, see Beilock, Wierenga, & Carr, 2003). Accordingly, expert performance is suggested to be supported by proceduralized representations, which do not rely on attentional control, as opposed to representations of novices that are more declarative in nature. During skill acquisition, these mechanisms are proposed to change based on changes in the learner's representation of the skill. Specifically, during skill acquisition and development, the representation of a novice is thought to change toward the proceduralized representation of an expert (Beilock, Wierenga, & Carr, 2002).

In addressing this, Beilock and Carr (2001) investigated attention and memory processes that support motor skill execution. Specifically, in order to learn about differences in underlying representations, generic knowledge (i.e., general memory: prescriptive information about a movement) and episodic knowledge (i.e., specific memory: autobiographical record of a particular performance) of novices and experienced golfers on the putting movement were explored. These different types of skill knowledge served as indicators of the degree of elaboration and proceduralization seen in the golfers' underlying representations. According to the authors' rationale, with increasing expertise, generic knowledge of the putt was thought to increase as the representation of a movement becomes more elaborate. At the same time, episodic knowledge of the putt was suggested to decrease as the representation becomes more proceduralized, running primarily outside of working memory, and thus not leaving a retrievable episodic record of the task performance. Consistent with these assumptions, findings revealed that, indeed, experienced golfers gave more detailed generic descriptions of the putt, but less detailed episodic descriptions of particular putts, while the opposite was true for novices. From this, the authors concluded that automatized execution of a movement is controlled via proceduralized representations that reduce attention and working memory demands, thereby resulting in greater generic memory but reduced episodic recall.

Similarly, after having trained novices for 650 practice putts, Beilock et al. (2002) found episodic descriptions of trained novices to be similar in the number of reported steps to their generic descriptions. Specifically, whereas the generic descriptions of trained novices were similar to those of untrained novices, episodic descriptions were in between those of untrained novices and experienced golfers. This suggests that trained novices' representations became more proceduralized with practice. From this and other research, the cognitive mechanisms underlying skill execution are thought to change with skill development, with experienced performers relying on more proceduralized mental representations compared to novices.

To date, the mental representations underlying performance have been studied in a variety of disciplines using a broad spectrum of methods (see Hodges et al., 2007). One of the first studies in sport addressing the question whether domain-specific knowledge and task performance relate was that of French and Thomas (1987). In their study, the authors examined the relationship of basketball-specific knowledge and basketball skills in children using paper-and-pencil test. Based on their findings, namely better shooting skill and more basketball knowledge in expert players in comparison to novice players, the authors were one of the first to highlight the salient role of knowledge in skilled performance. More recently, in his work on differences in the classification and representation of context-specific problem states using specific sorting techniques and interview methods, Huber (1997) found that experts' nodes (i.e., central concepts) of representations possess more features compared to novices. Besides that, fewer connections between concepts have been found in novices. Furthermore, by way of categorization tasks, Allard and Burnett (1985) could show that experts adhere to functional principles when classifying problems while novices rather rely on superficial features. With the help of questionnaire methods and interviews, McPherson et al. have been able to reveal the organization of movement knowledge for tennis (e.g., McPherson & Kernodle, 2003; McPherson & Thomas, 1989) and a variety of other sport domains (e.g., French & McPherson, 1999, 2004). From this and other research, findings suggest that experts maintain more refined mental representations for specific domains, and that such elaborate representations allow for a more refined execution of appropriate actions relative to novices (e.g., Ericsson, 2007; Ericsson & Smith, 1991; Ericsson & Towne, 2010).

Early research on object representations (e.g., Hoffmann, 1986; Rosch, 1978; Rosch & Mervis, 1975) suggests that knowledge is represented in taxonomies of hierarchically organized memory structures. Furthermore, these representations are suggested to provide the functional basis for the everyday interaction with objects (e.g., Hoffmann, 1990). Similarly, the cognitive action architecture approach (CAA-A, Schack, 2004; Schack & Mechsner, 2006; Schack & Ritter, 2009) suggests that the mental representations of high-level motor skills are also organized within hierarchical memory structures comprised of basic action concepts (BACs). Analogous to the well-established notion of basic concepts in the world of objects (e.g., Mervis & Rosch, 1981), BACs denote the cognitive compilation of body postures along with their sensory consequences that are functionally related to the attainment of action goals. From such an action architecture perspective, mental representations can be characterized by well integrated networks of action concepts that serve as tools to facilitate the controllability of the motor action system (e.g., Bläsing, Schack, & Brugger, 2010; Bläsing et al., 2009; Schack & Ritter, 2009).

By way of an experimental approach, Schack and Mechsner (2006) studied the tennis serve in high-level experts compared to low-level and non-tennis players in order to investigate the nature and role of long-term memory in skilled athletic performance. Employing structural dimensional analysis of mental representation (SDA-M; Schack, 2004, 2012), the authors analyzed representational frameworks for the tennis serve, and found that the structures of the experts' representations were organized in a distinctive tree-like hierarchy, were remarkably similar across individuals, and were well matched with the functional and biomechanical demands of the task. In comparison, the structures of mental representations in low-level players and non-players were organized in a less distinctive tree-like hierarchy, were much more variable across individuals, and were not as well matched with the functional and biomechanical demands of the task.

These results have been shown to generalize across a variety of complex motor skills such as in dancing (e.g., Bläsing, 2010; Bläsing et al., 2009), judo (e.g., Weigelt et al., 2011), volleyball (e.g., Velentzas et al., 2010), wind surfing (e.g., Schack & Hackfort, 2007), and manual action (e.g., Stöckel et al., 2012). Moreover, recent research on mental representations in special populations such as children and stroke patients (e.g., Braun et al., 2007; Stöckel et al., 2012) suggests that cognitive structures differ across both skill-levels and age. For example, Stöckel et al. (2012) examined the development of mental representations of grasp postures in children of different ages.

Similar to the characteristics of experts' mental representations, the authors found 9-year-old children's mental representations to be hierarchically organized according to the function of the grasp postures. Specifically, 9-year-old children's mental representation structures reflected distinct differences between comfortable and uncomfortable grasp postures, whereas 7-year-old and 8-year-old children's mental representations were less structured, and did not indicate any distinct differentiation between comfortable and uncomfortable grasp postures. From these results, the authors concluded that mental representations develop as a function of age, such that a child's ability to successfully distinguish between a comfortable and an uncomfortable grasp posture seems to mature on the basis of developing cognitive structures.

Differences in the mental representation across skill-levels and age suggest the idea that motor learning leads to functional adaptations in one's mental representation of a motor skill. That is, novices' unstructured mental representations are thought to develop into more refined and elaborate representations during the process of learning. This is in line with the general idea of learning within the cognitive architecture framework. From such a perspective, learning is a product of modifying and developing the mediating conceptual structures (BACs) within the memory system (Schack, 2004; Schack & Ritter, 2013). However, to date, research has largely focused on the differences between intact groups (e.g., novices and experts) using a between-subjects approach. If we assume that learning results in the modification and development of mental representations, then changes in one's representational structure should be evident over the course of skill acquisition. Therefore, we examined the potential for one's mental representation to functionally adapt to the biomechanical demands of the task during early skill acquisition as a consequence of task practice. By creating an experimentally induced controllable learning situation, we examined whether performance improvement is accompanied by order formation of action-related knowledge in long-term memory. It was predicted that, along with performance improvements, changes to the underlying mental representation would be evident as a consequence of skill acquisition. Specifically, it was predicted that during the course of learning, the initial unstructured mental representation of a novice practice group would elicit structural changes in the form of clusters of BACs which are related to the movement and its phases. Furthermore, it was predicted that the structural changes would reflect development toward the representation structure of expert performers (i.e., functional adaptations). In contrast, a novice control group, which does not partake in task practice, was predicted to show no changes to their initial unstructured mental representation.

2.2 Methods

2.2.1 Participants

Twenty-four students (12 women, 12 men; M_{age} = 27.3 years, SD = 5.9) participated in the present study. All participants were novice golfers with no previous golf experience. They were randomly assigned to either a practice group (n = 12, M_{age} = 26.08 years, SD = 4.48, 6 male) or a control group (n = 12, M_{age} = 28.50 years, SD = 6.95, 6 male), who did not practice the putting task. The study was conducted in accordance with local ethical guidelines, and conformed to the declaration of Helsinki.

2.2.2 Structural dimensional analysis of mental representation

Although various methods that allow for the study of knowledge-based mental representation structures of movements in long-term memory exist (for an overview, see Hodges et al., 2007), most of them are non-experimental and focus on explicit knowledge (e.g., interviews, questionnaires, paper-and-pencil tests). Aiming at an experimental approach in which subjects are not asked to give explicit statements on their representation structure, Schack (2012) introduced structural dimensional analysis of mental representation (SDA-M). This method provides psychometric data on the structure and dimension of mental representations of complex movements in long-term memory.

The SDA-M consists of four steps: In a first step, a split procedure delivers a distance scaling between the BACs of a suitably predetermined set. In a second step, a hierarchical cluster analysis is used to outline the structure of the given set of BACs. In a third step, a factor analysis reveals the dimensions in this structured set of BACs, and in a last step, the cluster solutions are tested for invariance within and between groups (for details, see Schack, 2012).

2.2.3 Selected complex movement and its structure

The putt in golf is considered one of the most important parts of the game as it represents 43% of all golf shots taken during a round of golf (Pelz & Frank, 2000). For the purpose of the present study, BACs of golf putting were utilized. In order to specify the BACs of the chosen movement, the following steps were necessary: First, the movement and movement phases were described in detail with the help of standard textbooks (e.g., Hamster, 2008; Pelz & Frank, 2000) and the biomechanical analysis of the golf putt. The parts of the movement considered most relevant resulted in a preliminary set of 27 meaningful body postures. The 27 body postures were further rated and verified by golf experts[5] (n = 5). In a last step, a final set of 16 BACs were selected based on the experts' ratings.

Based on the procedure described above, the following 16 BACs for the putt were identified: (1) shoulders parallel to target line, (2) align club face square to target line, (3) grip check, (4) look to the hole, (5) rotate shoulders away from the ball, (6) keep arms-shoulder triangle, (7) smooth transition, (8) rotate shoulders toward the ball, (9) accelerate club, (10) impact with the ball, (11) club face square to target line at impact, (12) follow-through, (13) rotate shoulders through the ball, (14) decelerate club, (15) direct clubhead to planned position, (16) look to the outcome.

From a functional and biomechanical perspective (cf. Göhner, 1992, 1999), each of the 16 BACs can be assigned to a particular movement phase: preparation (BAC 1-4), backswing (BAC 5-7), forward swing (BAC 8-11), and attenuation (BAC 12-16). In other words, the first phase (i.e., preparation phase) consists of the performer setting up and aligning her/ his body to the hole. The second phase (i.e., backswing) consists of the start of the backswing and transition between back and forward swing. The third phase (i.e., forward swing) relates to the acceleration of the clubhead as well as to the mechanical and functional qualities associated with

[5] Teaching professionals from different golf clubs in Germany.

clubhead-ball impact. Finally, the attenuation phase consists of the follow through and evaluation of the outcome.

2.2.4 Apparatus and task

A standard putter and golf ball were used in the present study. Putts were performed on an artificial indoor putting green to a target three meters away from the starting point. Participants were instructed to putt a golf ball as accurately as possible to the target, on which the ball was supposed to stop.[6] Instead of a hole, a target was chosen for the present study, in order to measure two-dimensional error scores as opposed to hits only. The target was marked by a circle 10.8 cm (4.25 in) in diameter in accordance with the size of a regulation golf hole. In order to record the outcome of each golf putt, a video camera was positioned above the target to capture a top-down view of the final ball position after each putt (field of view: 3.3 m × 1.8 m).

Mental representation structure was assessed using a splitting task, first step of the above described SDA-M, in order to learn about the distance between BACs in memory. This splitting task was performed in front of a computer with the screen displaying the BACs of the golf putt. In detail, the splitting task proceeds as follows: one selected basic action concept is permanently displayed on the screen (anchor concept) while the rest of the basic action concepts are presented successively in randomized order; participants are asked to decide, one after another, whether a given basic action concept is related to the anchor concept or not during movement execution; once a given list of BACs is finished, the next BAC serves as an anchor concept and the procedure continues. The splitting task ends after each BAC has been compared to the remaining BACs in the list.

2.2.5 Procedure

The present study consisted of three test days (pre-, post-, retention-test) and an acquisition phase (see Table 2.1).

[6] Although skilled golfers use a strategy of putting past the hole, requiring our novice participants to attempt to stop the ball on the target was not assumed to negatively interfere with performance, as the novices would have not previously developed the strategy of putting past the hole.

Table 2.1

Design of the study including three test days and an acquisition phase

	Pre-test	Acquisition			Post-test	Retention-test
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 8
Practice group (*n* = 12)	SDA-M Putting task	Putting practice			SDA-M Putting task	SDA-M Putting task
Control group (*n* = 12)	SDA-M -	-			SDA-M -	SDA-M -

Note: SDA-M: structural dimensional analysis of mental representation; putting task: 3 x 20 putts, putting practice: 10 x 20 putts each day.

2.2.5.1 Pre-test

On the first day, participants signed informed consent forms. In order to become familiar with the movement, all participants watched a video of a skilled golfer performing the putting task. Next, the experimenter introduced the participant to the splitting task. First, each participant was presented a randomized list of the 16 BACs of the putt. The experimenter explained the meaning of each of the 16 BACs to the participant in order to ensure comprehension. Next, the participants read the instructions on the screen for how to complete the splitting task. Specifically, participants were instructed to decide whether the basic action concepts are related to one another or not during movement execution. Following, the participants completed the splitting task to determine their starting mental representation structures of the putt. Furthermore, the practice group then performed three blocks of 20 putts each to assess their starting performance level. Participants were instructed to putt a golf ball as accurately as possible to the target, on which the ball was supposed to stop. The control group did not perform the putting task. Finally, each participant was asked to not consult any information on golf in general and the putt in particular for the duration of the experiment.

2.2.5.2 Acquisition phase

The next three days, participants of the practice group performed the putting task 10 blocks of 20 putts each day with a short break between every two blocks. No feedback on technical issues was given during putting. The only feedback available for the participant was that of the visible outcome (i.e., knowledge of result). The control group did not practice during this time.

2.2.5.3 Post-test and retention-test

During post-test (day five) and retention-test (day eight) all participants completed the splitting task again to determine their final mental representation structures of the putt movement. Next, participants of the practice group performed three blocks of 20 putts once more to assess their final outcome performance. The control group again did not perform the putting task.

2.2.6 Data analysis

2.2.6.1 Performance

Putting performance was measured by (a) accuracy, (b) bias, and (c) consistency. The accuracy, bias, and consistency of outcomes were assessed using two-dimensional error scores based on the x and y coordinates of each putt using the center of the target as the origin of the axes (see Hancock, Butler, & Fischman, 1995). More specifically, accuracy was measured by the mean radial error (MRE), which was defined as a subject's average distance each putt came to the center of the target in mm. Bias was represented by subject-centroid radial error (SRE). SRE was defined as the radial distance of the subject's centroid from the center of the target in mm. A subject's centroid is a positionally typical shot whose coordinates are given by the average x and average y value of a subject's shots in mm. Consistency was measured by bivariate variable error (BVE). BVE is analogous to variable error in one-dimensional analyses, and was defined as the square root of a subject's k shots' mean squared distance from their centroids in mm. To examine performance during acquisition phase, a 3 (*day*) × 10 (*block*) within-subjects analysis of variance

(ANOVA) was calculated for each of the dependent variables. Additionally, performance from pre- to post- and retention-test was examined using a 1 (*group*) × 3 (*time of measurement*) within-subjects ANOVA for each of the dependent variables. For post-hoc analysis, paired t-tests were conducted employing a Bonferroni correction (α = .017) to account for the inflation of type I errors. Cohen's *d* was used as an estimator of effect size (Cohen, 1992).

2.2.6.2 Mental representation structure

Mental representation structure was measured by calculation of mean group dendrograms via cluster analysis (i.e., by summing the Z-matrices of the individuals; for more details see Schack, 2012). For all cluster analyses conducted, an alpha-level of $\alpha = .05$ was chosen, which resulted in a critical value $d_{crit} = 3.41$. Links between BACs above this critical value were considered as statistically irrelevant. In other words, BACs linked above this line were treated as being not related, while BACs linked below this line resulted in a cluster and therefore were treated as being statistically related. Analyses of invariance were conducted in order to compare differences between cluster solutions. According to Lander (1991, 1992; see Schack, 2012), two cluster solutions are variant, that is significantly different, for $\lambda < .68$, while two cluster solutions are invariant for $\lambda \geq .68$. In addition, the adjusted rand index (ARI; Rand, 1971; Santos & Embrechts, 2009) was used to examine the similarity between the practice groups' mental representation and that of expert performers. The adjusted rand index serves as an index of similarity on a scale from -1 to 1. On this scale, the value "-1" indicates that two cluster solutions are different and the value "1" indicates that two cluster solutions are the same. Indices between these extremes rank similarity between two cluster solutions. As a reference structure, mental representations of two experts were used which reflected well the four movement phases (i.e., preparation, backswing, forward swing, and attenuation) of the putt.

2.3 Results

2.3.1 Performance

2.3.1.1 Acquisition phase

A 3 × 10 within-subjects ANOVA on MRE indicated a significant main effect of *day*, $F(2,22) = 23.76$, $p = < .001$, $\eta_p^2 = .68$, as well as a significant main effect of *block*, $F(9,99) = 13.46$, $p < .001$, $\eta_p^2 = .55$ (see also Figure 2.1). The *day* by *block* interaction, $F(18,198) = 1.11$, $p = .384$, $\eta_p^2 = .09$, was not significant. For bias, a 3 × 10 within-subjects ANOVA on SRE revealed a significant main effect of *block*, $F(9,99) = 8.04$, $p < .001$, $\eta_p^2 = .42$. The main effect of *day*, $F(2,22) = 2.49$, $p = .106$, $\eta_p^2 = .19$, as well as the *day* by *block* interaction, $F(18,198) = 1.35$, $p = .163$, $\eta_p^2 = .11$, were not significant. For consistency, a 3 × 10 within-subjects ANOVA on BVE revealed a significant main effect of *day*, $F(2,22) = 18.61$, $p < .001$, $\eta_p^2 = .63$, as well as a significant main effect of *block*, $F(9,99) = 14.19$, $p < .001$, $\eta_p^2 = .56$. The *day* by *block* interaction, $F(18,198) = 1.30$, $p = .189$, $\eta_p^2 = .11$, was not significant. Thus, for the two dependent variables MRE and BVE, performance improved both over acquisition days as well as within acquisition days, while for SRE performance improved only between acquisition days.

2.3.1.2 Pre-, post-, and retention-test

Table 2.2 presents means, standard deviations, and confidence intervals at pre-, post- and retention-test for the three dependent variables (accuracy, bias, and consistency) for the practice group. With respect to accuracy, a within-subjects ANOVA on MRE revealed a significant effect of *time of measurement*, $F(2,22) = 76.15$, $p < .001$, $\eta_p^2 = .87$. Post-hoc analyses indicated that MRE decreased significantly from pre-test to post-test, $t(11) = 8.49$, $p < .001$, $d = 1.60$, and from pre-test to retention-test, $t(11) = 11.61$, $p < .001$, $d = 2.53$, but not from post-test to

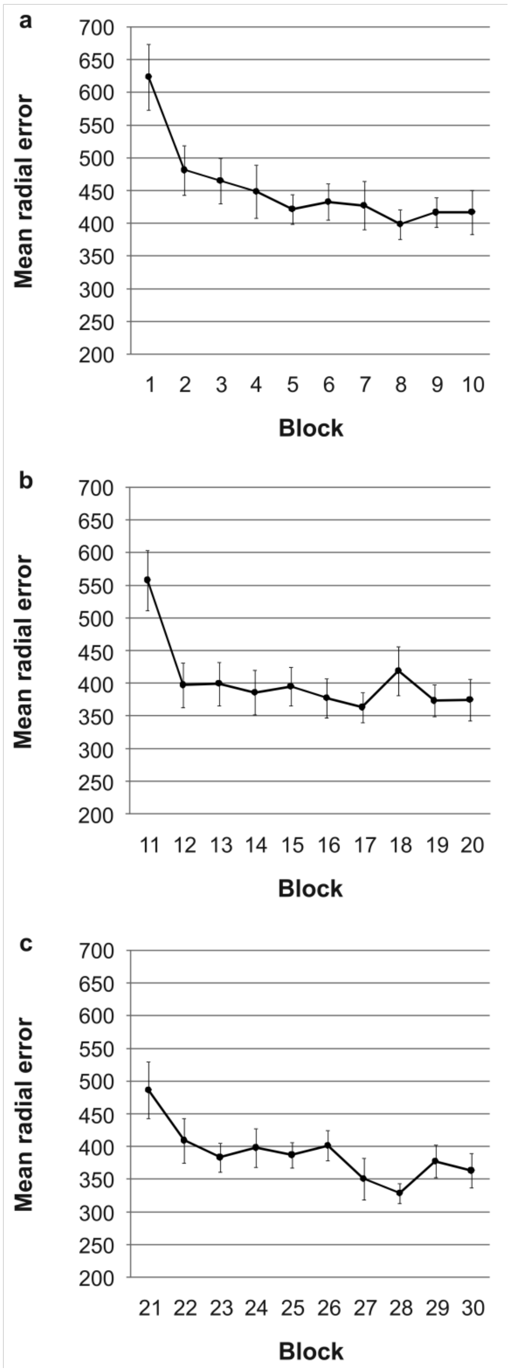


Figure 2.1. Mean radial error in mm per block for the practice group during acquisition phase (i.e., three consecutive days of practice; a = day 1, b = day 2, c = day 3). Error bars represent standard errors.

retention-test, $t(11) = 2.79$, $p = .018$, $d = .54$. For bias, a within-subjects ANOVA on SRE revealed no significant effect of *time of measurement*, $F(2,22) = .67$, $p = .500$, $\eta_p^2 = .06$. Consequently, participants did not differ in their magnitude of bias after task practice. For consistency, a within-subjects ANOVA on BVE revealed a significant effect of *time of measurement*, $F(2,22) = 73.31$, $p < .001$, $\eta_p^2 = .87$. Pairwise comparisons indicated that BVE decreased significantly from pre-test to post-test, $t(11) = 8.06$, $p < .001$, $d = 1.37$, and from pre-test to retention-test, $t(11) = 11.72$, $p < .001$, $d = 2.08$, as well as from post-test to retention-test, $t(11) = 2.90$, $p = .014$, $d = .48$.

Table 2.2

Descriptive statistics for performance outcome variables across pre-test, post-test, and retention-test for the practice group in cm (n = 12)

	Pre-test		**Post-test**		**Retention-test**	
	M (SD)	95% CI	*M (SD)*	95% CI	*M (SD)*	95% CI
MRE	63.20 (11.92)	[55.63, 70.77]	43.99 (12.04)	[36.34, 51.64]	38.78 (6.65)	[34.60, 43.01]
SRE	13.23 (10.93)	[6.29, 20.18]	8.95 (7.73)	[4.04, 13.86]	10.60 (8.32)	[5.31, 15.89]
BVE	72.22 (15.99)	[62.06, 82.38]	50.60 (15.53)	[40.74, 60.74]	44.33 (10.26)	[37.81, 50.85]

Note: MRE = mean radial error (accuracy); SRE = subject-centroid radial error (bias); BVE = bivariate variable error (consistency); CI = confidence interval.

2.3.2 Mental representation structure

As can be seen in Figure 2.2, cluster analysis revealed little to no clustering in the mean group dendrograms of each group at pre-test (with critical value $d_{crit} = 3.41$). More specifically, the control group's dendrogram revealed no significant clusters of BACs, while the practice group's dendrogram displayed only a single cluster pertaining to aspects of movement preparation, that is to say BAC 2 (align club face square to target line) and BAC 3 (grip check). In comparison to the reference structure, both dendrograms reflected a very different structure, with the adjusted rand index being zero for the control group and close to zero (ARI = .11) for the practice group.

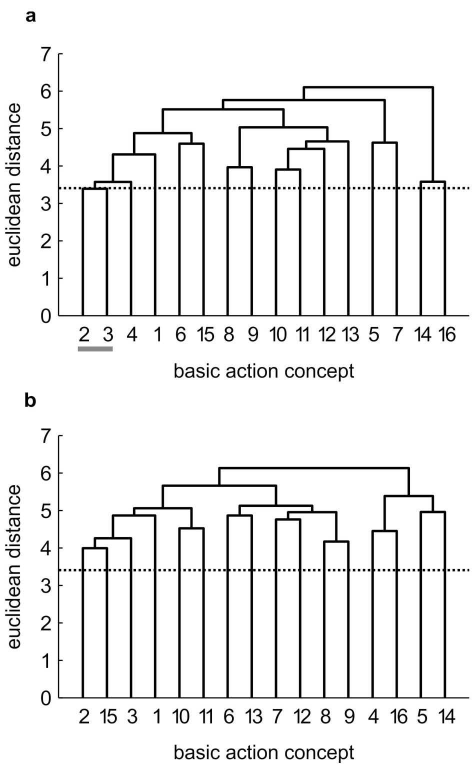


Figure 2.2. Mean group dendrograms of (a) the practice group (*n* = 12) and (b) the control group (*n* = 12) for the golf putt at pre-test. The numbers on the *x*-axis relate to the BAC number, the numbers on the *y*-axis display Euclidean distances. The lower the link between related BACs, the lower is the Euclidean distance. The horizontal dotted line marks d_{crit} for a given α-level ($d_{crit} = 3.41$; α = .05): links between BACs above this line are considered not related; horizontal grey lines on the bottom mark clusters. BACs: (1) shoulders parallel to target line, (2) align club face square to target line, (3) grip check, (4) look to the hole, (5) rotate shoulders away from the ball, (6) keep arms-shoulder triangle, (7) smooth transition, (8) rotate shoulders towards the ball, (9) accelerate club, (10) impact with the ball, (11) club face square to target line at impact, (12) follow-through, (13) rotate shoulders through the ball, (14) decelerate club, (15) direct clubhead to planned position, and (16) look to the outcome.

While no discernible structure existed for the practice group at baseline (i.e., pre-test), significant changes were observed after substantial task practice. More specifically, during pre-test examination, the group's mean dendrogram displayed only one cluster of basic action concepts. However, post-test examination as well as for retention-test examination of the group's mean dendrograms uncovered an increase in the number of functional clusters (see Figure 2.3). Statistical analyses of invariance revealed significant differences between pre-test and post-test (λ = .32) as well as between pre-test and retention-test (λ = .31). The BACs have become clustered into three functional units pertaining to the movement preparation phase and the swing phase. One cluster denoted the preparation of the putt with BAC 1 (shoulders parallel to target line), BAC 2 (align club face square to target line), BAC 3 (grip check), and BAC 4 (look to the hole). A second cluster related to aspects of the forward swing with BAC 8 (rotate shoulders toward the ball) and BAC 9 (accelerate club). Lastly, a third cluster related to clubhead-ball impact as indicated by a cluster including BAC 10 (impact with the ball) and BAC 11 (club face square to target line at impact).

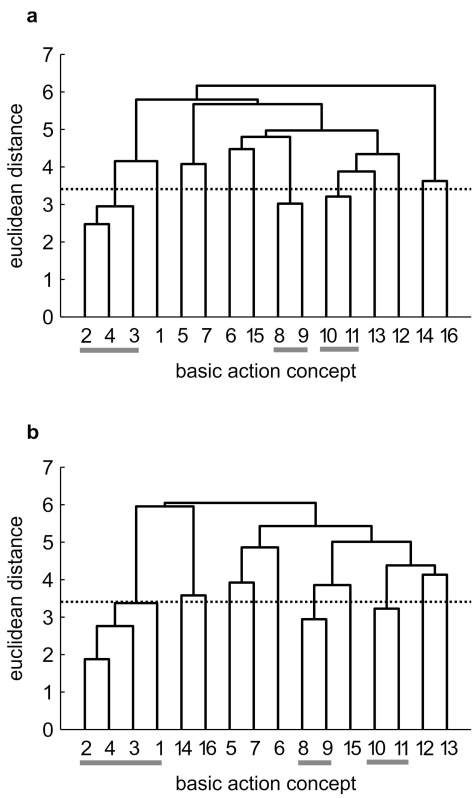


Figure 2.3. Mean group dendrograms of the practice group for the golf putt at (a) post-test and (b) retention-test (n = 12; α = .05; d_{crit} = 3.41).

Although the dendrograms for the post-test and retention-test both displayed a three cluster solution, one slight difference existed between the post-test and retention-test dendrogram. Namely, for the preparation phase, the post-test dendrogram consisted of three BACs (BAC 2: align club face square to target line; BAC 3: grip check; BAC 4 - look to the hole), however, the dendrogram for the retention-test included one additional BAC (BAC 1: shoulders parallel to target line). Despite this slight difference, the two cluster solutions of post-test and retention-test are statistically considered the same ($\lambda = .68$).

To assess the degree of functional adaptation, the mental representations of the practice group were compared to the mental representation of expert golfers ($n = 2$). The adjusted rand index indicated that over the course of practice, the mean dendrograms of the practice group became more similar to those of experts. Specifically, when being compared to an expert structure, the mean dendrograms of the practice group developed from pre-test (ARI = .11) to post-test (ARI = .49) and retention-test (ARI = .70), with the adjusted rand index approaching the value "1". That is, the cluster solutions became more similar to the reference structure (i.e., expert structure) over time.

For the control group, results revealed no changes in the group's mental representation structure for the putt. More specifically, for pre-test as well as for post- and retention-test the group's mean dendrograms indicated no clustering of basic action concepts (see Figure 2.4). When being compared to the expert structure, the mean dendrograms of the control group did not indicate any development over time (ARI = 0 for pre-, post-, as well as retention-test). Each of the 16 BACs of the putting movement were treated as independent across pre-, post-, and retention-testing.

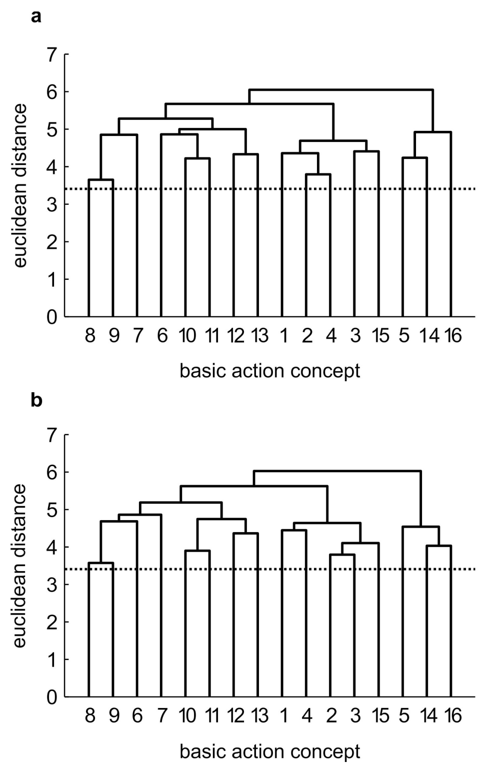


Figure 2.4. Mean group dendrograms of the control group for the golf putt at (a) post-test and (b) retention-test (n = 12; α = .05; d_{crit} = 3.41).

2.4 Discussion

In the present study, we examined the development and change in both performance and the structure of the mental representation of a complex movement during early skill acquisition. The results clearly demonstrate order formation of action-related knowledge in long-term memory (i.e., changes in mental representation structure) that comes along with improvements in outcome performance over the course of practice.

With respect to outcome performance, accuracy as well as consistency increased significantly over the course of the study.[7] That is, participants in the practice group did not only become more accurate, but also more consistent in their putting performance. Thus, as we expected, novice golfers' outcome performance became better with practice. This result is in line with the power law of practice (e.g., Newell & Rosenbloom, 1981; Schmidt & Lee, 2005). The power function and its logarithmic relationships between practice trials and performance state that performance increases as a function of practice. According to Schmidt and Lee (2005), this is especially true for novices since, when being new to a task, there is much room left for improvement. Moreover, since performance improvements recorded at post-test persisted throughout retention-test, it can be stated that improved outcome performance reflects skill acquisition as a result of motor learning.

With respect to mental representation structure, the practice group's structure elicited changes over the course of practice while the control group, without practice, did not show changes in their mental representation structure. Consistent with our predictions, following practice the group dendrogram of the practice group indicated several meaningful clusters relating to the functional phases of the movement (i.e., preparation and forward swing). Moreover, the observed changes revealed a trend toward the representational structure of experts as shown by increases in adjusted rand indices from pre-, to post-, and to retention-test. Thus, the results of the present study clearly demonstrate that practice results in functional adaptations in the mental representation of complex action. That is, motor learning in early skill acquisition is accompanied by order formation of action-related knowledge in the direction of a functional structure of the movement.

These findings extend those of Schack and Mechsner (2006) as well as those of Bläsing et al. (2009) who showed differences in mental representation structure in relation to differences in skill level. In these studies, high skill-level was characterized by high order formation, whereas low skill-level was characterized by low order

[7] Although accuracy and consistency increased significantly, a change in bias was not significant. This finding was due to the distribution of putts being dispersed uniformly about the hole in both the pre-test and post-test.

formation. Contrary to such cross-sectional designs, a longitudinal design was chosen for the present study. In doing so, the present study was the first to show that the mental representation of a complex movement not only differs between subjects according to skill level, but develops over time within subjects during skill acquisition. The changes observed in the mental representation structures in the present study highlight initial functional order formation. In other words, preliminary increases in skill level were accompanied by initial changes in the mental representation structure toward an expert structure.

The findings of the present study fit well into the large body of research on the learning of perceptual-motor skills, and especially the concept of different stages of skill acquisition (e.g., Anderson, 1982, 1995; Fitts & Posner, 1967). According to Fitts and Posner (1967) proposing three phases of skill learning (cognitive, associative, and autonomous), skill acquisition starts with an early cognitive phase in which a novice attempts to understand a task and its demands regardless of whether the attempts are guided or not. In collecting information and acquiring knowledge, rules may develop resulting in order formation of action-related knowledge, and thus in a functional mental representation structure.

Interestingly, while mental representation structures developed over the course of practice, no information on the movement was given besides that provided by the video prior to the pre-test. That is, participants of the practice group received no explicit instructions in terms of movement technique. This gives rise to the assumption that changes in mental representation structure take place during the process of learning without explicit guidance on what to pay attention to and how to perform the movement. This observation is in line with findings from other studies, suggesting that novices are able to accumulate knowledge that directs their performance, even in the absence of explicit instructions (e.g., Hardy, Mullen, & Jones, 1996). Relating to this, it is currently not clear to what extent explicit or implicit learning processes (cf. Masters, 1992) contribute to the development of mental representation structure of complex actions. Examining the effect of these learning strategies on skill representation may be a fruitful direction for future research.

It is also important to note that, besides showing that repeatedly executing a movement leads to functional adaptations in one's mental representation, we were able to show, on the other hand, that not executing a movement does not lead to functional adaptations in one's mental representation. Specifically, the mental representation of the control group did not reveal any structure, neither at pre-test, post-test, or retention-test, and thus did not change. Hence, with the longitudinal design of the study, we were the first to show that participants, who were not practicing the task, revealed stable unstructured representations over time. Consequently, participants did not learn from the method itself. Taken together, by showing that the representation structure of the control group did not change over time, we were able to demonstrate that SDA-M is a reliable method for the investigation of representation structures over time.

A potential limitation in the current study was that we did not examine whether the learned skill transfers to a related task. To this extent, we only focused on the persistence of the acquired skill over time, through the use of a retention-test. Specifically, we retested subjects after a retention interval of 72 h in order to differentiate between immediate performance improvements and persistent performance improvements (i.e., learning). However, it would be valuable to test for transfer in future studies, in order to examine whether the extent of skill transfer relates to mental representation structure. Moreover, investigating the relationship of performance and underlying mental representations on an individual level, rather than group level, may prove to be a valuable objective for future research. Specifically, future research should address the extent to which the degree of improvement in an individual's performance over practice coincides with the degree of development in their individual mental representation.

To conclude, with the present study it was possible to answer the question if, during early stages of skill acquisition, performance improvement of a complex movement is accompanied by changes in the structure of one's mental representation in long-term memory. According to our results, order formation in mental representation structure develops in novices practicing a complex skill. Although the results of the present study exclusively relate to early skill acquisition, it is proposed that such changes in mental representation structure will proceed during further skill acquisition. It would be of interest to learn more about the evolution and the progress of order formation of action-related knowledge, and its relation to learning curves, both on a group as well as an individual level. Therefore, changes in mental representation structure over the course of learning up to a suitable functional and high-level order formation will be a key issue for future research. Specifically, to examine ways to facilitate the development of mental representation structure during learning will be a main objective in the future. Focusing on the role of the structure of one’s mental representation will hopefully shed further light on how to pave the way to expertise, the way to both high-level order formation and high-level performance.

3 MENTAL PRACTICE AND THE DEVELOPMENT OF MENTAL REPRESENTATION STRUCTURE

This chapter is based on the manuscript

Frank, C., Land, W. M., Popp, C., & Schack, T. (2014). Mental representation and mental practice: Experimental investigation on the functional links between motor memory and motor imagery. *PLoS ONE, 9*, e95175.

Abstract

Recent research on mental representation of complex action has revealed distinct differences in the structure of representational frameworks between experts and novices. More recently, research on the development of mental representation structure has elicited functional changes in novices' representations as a result of practice. However, research investigating if and how mental practice adds to this adaptation process is lacking. In the present study, we examined the influence of mental practice (i.e., motor imagery rehearsal) on both putting performance and the development of one's representation of the golf putt during early skill acquisition. Novice golfers (N = 52) practiced the task of golf putting under one of four different practice conditions: mental, physical, mental-physical combined, and no practice. Participants were tested prior to and after a practice phase, as well as after a three day retention interval. Mental representation structures of the putt were measured, using the structural dimensional analysis of mental representation. This method provides psychometric data on the distances and groupings of basic action concepts in long-term memory. Additionally, putting accuracy and putting consistency were measured using two-dimensional error scores of each putt. Findings revealed significant performance improvements over the course of practice together with functional adaptations in mental representation structure. Interestingly, after three days of practice, the mental representations of participants who incorporated mental practice into their practice regime displayed representation structures that were more similar to a functional structure than did participants who did not incorporate mental practice. The findings of the present study suggest that mental practice promotes the cognitive adaptation process during motor learning, leading to more elaborate representations than physical practice only.

3.1 Introduction

According to skill acquisition theories, cognitive mechanisms governing skill execution develop over the course of learning (e.g., Anderson, 1982, 1993, 1995; Fitts & Posner, 1967; Magill, 2011). To this extent, skill acquisition is known to be accompanied by both overt changes (i.e., performance improvements) and covert changes (i.e., cognitive improvements) over time. Of particular interest for skill acquisition is the role that mental representations play in the learning and control of actions. Individuals of different skill levels have been suggested to differ not only in their overt performance (e.g., Newell & Rosenbloom, 1981), but also in their underlying skill representations in long-term memory (e.g., Allard & Burnett, 1985; Ericsson & Smith, 1991; French & Thomas, 1987; Huber, 1997; McPherson & Thomas, 1989). Consequently, an individual's mental representation of a motor skill is thought to change on his/her way to expertise, namely in the direction of an elaborate, well-developed representation (e.g., Ericsson, 2007).

Knowledge-based mental representation structures in long-term memory have been measured using a variety of different methods (for an overview, see Hodges et al., 2007). One approach, which specifically takes into account the cognitive level of motor actions, is the cognitive action architecture approach (CAA-A; e.g., Schack, 2004; Schack & Mechsner, 2006; Schack & Ritter, 2009). According to this approach, motor learning can be characterized as the modification and adaptation of representational frameworks of complex actions in memory. Representational frameworks are comprised of basic action concepts (BACs; i.e., cognitive chunks of movement postures and their sensory consequences within the realization of an action goal), which reflect the building blocks of an action in long-term memory.

Early research on representational frameworks of complex action has elicited distinct differences in the mental representation between experts and novices. Schack and Mechsner (2006), for example, investigated representational frameworks of the tennis serve in expert and non-expert tennis players using structural dimensional analysis of mental representation (SDA-M; e.g., Schack, 2004, 2012). Findings revealed distinct differences between the mental representation of expert and novice tennis players such that experts' structures were more elaborate than novices' structures. More specifically, whereas the mental representations of experts were organized hierarchically and structured in a functional way (i.e., BACs being grouped according to the functional and biomechanical demands of the tennis serve), the mental representations of novices were not. Moreover, novices' mental representations varied greatly in their structure, while those of experts were more similar. From this, the authors concluded that such elaborate skill representations in long-term memory play a salient role in skilled action. Up to now, distinct differences in representational frameworks of complex action have been demonstrated across a variety of sports, such as dance (e.g., Bläsing et al., 2009), volleyball (e.g., Velentzas et al., 2010), and windsurfing (e.g., Schack & Hackfort, 2007). Furthermore, the results have been shown to generalize to developmental aspects of manual action (e.g., Stöckel et al., 2012), and to special populations (e.g., Braun et al., 2007).

More recently, Frank, Land, and Schack (2013) examined if and how representational frameworks of complex action change over the course of practice in early skill acquisition. Specifically, a group of novices practiced a putting task over the course of three days, whereas a control group did not putt at all. Mental representation structures were recorded prior to and after practice as well as after a three-day retention interval. Results indicated that neither of the groups' mental representations revealed any meaningful structure of the putt prior to practice. However, along with performance improvements, changes in the mental representation structure were evident for the practice group. Specifically, after substantial putting practice, the mental representation of the practice group revealed a structure that reflected key parts of the movement phase pertaining to the functional and biomechanical demands of the task. For the control group, however, no changes in mental representation of the putt were evident from pre-, to post- and to retention-test. From this, it was concluded that the acquisition of motor skills is associated with functional adaptations of the representational frameworks in long-term memory. In addition to the research showing the changes in mental representation over the course of skill acquisition, more recently, Land, Frank, & Schack (2014) demonstrated that the type of instructions given to novices during learning (here: internal vs. external focus) can influence the rate of representation development. Results indicated that learners instructed to adopt an external focus of attention performed with greater putting accuracy and consistency, while also revealing a greater degree of development in their mental representation of the putting task.

Interestingly, while instructional type has been shown to influence the development of mental representations during skill acquisition, research to date has yet to consider the influence that mental practice can have on this process. As an important means to promote motor skill acquisition, mental practice has received a great deal of attention in the last 50 years within cognitive sport psychology. Mental practice in the sense of motor imagery rehearsal refers to the act of repeatedly simulating (i.e., imagining) a motor action in one's mind without actually executing it at the same time (e.g., Jeannerod, 1994, 1995, 2004; Moran, Guillot, MacIntyre, & Collet, 2012). Unlike perception, imagery can be understood as the creation or re-creation of real-world experiences in the absence of the actual sensory stimuli (e.g., Annett, 1995a; Farah, 1984; Morris et al., 2005). Accordingly, in contrast to actual or physical practice, which implies overtly rehearsing a motor action, mental practice in the sense of motor imagery rehearsal refers to the covert rehearsal of a motor action by way of imagery.

Up to now, mental practice has proven to be an effective tool, both to improve performance and to promote learning (e.g., Driskell et al., 1994; Feltz & Landers, 1983; Feltz et al., 1988; Grouios, 1992; Hinshaw, 1991). Meta-analyses studying the effectiveness of mental practice have reported small to moderate effect sizes (i.e., d = .48 to d = .68), suggesting that mental practice, although not as effective as physical practice, significantly influences performance compared to no practice. While, to date, no meta-analysis exists that has thoroughly examined the effectiveness of a combination of physical and mental practice, findings from various studies support the superiority of such a combined type of practice on performance (e.g., Hall, Buckolz, & Fishburne, 1992; McBride & Rothstein, 1979; Stebbins, 1968). From this and other research, mental practice can be considered as an effective means to improve performance and to promote learning. Specifically, comparing the effectiveness of each practice type (i.e., combined practice (CP) – physical practice (PP) – mental practice (MP) – no practice (NP)), combined practice has been shown to be most effective, followed by physical practice, while mental practice is less effective than its physical counterpart, but more effective than no practice (i.e., CP > PP > MP > NP).

Researchers have suggested a variety of possible explanations for the underlying mechanisms of mental practice (for an overview, see Grouios, 1992; Morris et al., 2005). Two early theories offer two distinct perspectives, one focusing on more peripheral processes (i.e., psychoneuromuscular theory; Jacobson, 1931), and one focusing on more central mechanisms (i.e., symbolic learning theory; Sackett, 1934). The psychoneuromuscular theory (Jacobson, 1931) is centered around the activation of muscles during imagery. According to this theory, mental practice is thought to facilitate the performance and the learning of a movement such that it causes a similar activation pattern of muscles as during movement execution, which in turn aids subsequent movement execution. In contrast to this more peripheral motor explanation, the symbolic learning theory (Sackett, 1934), representing a cognitive explanation, proposes that the sequence of a movement is coded through symbols. Accordingly, mental practice is thought to facilitate performing a movement sequence through the repetition of symbolic components of the movement sequence resulting in a better symbolic representation.

More recently, the increasing interest in and findings from neurophysiological research have led to an explanation for the effects of mental practice which is known as the principle of functional equivalence (Finke, 1979; Jeannerod, 1994, 1995; Johnson, 1980). This principle focuses on central mechanisms as well, and as such proposes that the simulation of a movement (i.e., motor imagery) and the execution of a movement are functionally equivalent. Thus, as stated by the functional equivalence principle, mental practice to some extent involves the same underlying structures and covert processes as physical practice. Specifically, during motor imagery, the mental representation of a motor action is activated in order to enable the imager to imagine the movement, and it is stabilized as a result of repeatedly imagining the movement. In this sense, mental practice is thought to help improve performance and learning in a functionally equivalent way as physical practice does. Up to now, findings from neurophysiological research mainly support the functional equivalence between the simulation and the execution of an action (e.g., Decety, 1996; Jeannerod, 1994; Jeannerod & Decety, 1995; for a review, see Lotze & Halsband, 2006). Moreover, neurophysiological studies have shown that both mental and physical practice lead to significant changes in neural networks during skill acquisition (e.g., Lafleur et al., 2002; Ungerleider, Doyon, & Karni, 2002; Zhang et al., 2011; Zhang et al., 2012). However, although neurophysiological studies elicit changes in brain activation following mental practice, it is not clear, what these changes stand for on a cognitive representational level. Such changes in neurophysiological variables point to the idea that functional changes on a cognitive level (i.e., concept formation in one's mental representation) may take place during mental practice.

Taken together, while the acquisition of a complex motor skill by way of physical practice has been shown to be accompanied by the formation of representation structures in long-term memory, it is currently unclear how mental practice affects this representation formation process. Analogous to changes in brain activation on a neural level, mental practice may lead to functional adaptations in mental representation on a cognitive level. That is, we expect mental practice to add to the development of representation structures. Moreover, examining the effect of mental practice on both the overt level of performance and the covert level of mental representations in novices might help to gain more detailed understanding of the covert processes that do or do not lead to performance improvements and learning in early skill acquisition. To date, research examining how mental practice affects both overt motor performance and covert mental representation is lacking. Hence, with the present study, recreating the typical four groups mental practice design (for more details, see Feltz et al., 1988; Taktek, 2004), we aim at bridging this gap by examining the effects of mental practice on both the performance level and the mental representation level. In short, we examined how physical practice, mental practice, and a combination of both affect the performance and the development of one's mental representation of a golf putting task. Based on previous findings, it was predicted that putting performance would change according to type of practice such that combined practice would be superior to physical practice, which in turn would be superior to mental practice (i.e., CP > PP > MP > NP). Furthermore, it was predicted that, along with performance improvements, changes to the underlying mental representation would be evident as a consequence of skill acquisition. Specifically, it was predicted that novices' unstructured mental representation would turn into a more structured representation with practice. More importantly however, we were interested in what impact mental practice would have on mental representation development, and whether this related to performance.

3.2 Methods

3.2.1 Participants

Fifty-two students participated in the present study. All participants were novice golfers with no prior experience in golf. Each participant was randomly assigned to one of four groups: mental practice group (n = 13, M_{age} =23.15 years, SD = 2.28, 8 female), physical practice group (n = 13, M_{age} =24.54 years, SD = 3.64, 9 female), mental-physical combined practice group (n = 13, M_{age} = 23.69 years, SD = 2.93, 9 female) and no practice group (n = 13, M_{age} = 27.31 years, SD = 5.53, 8 female). The experimental procedure and written consent form for this study were approved by the ethics committee at Bielefeld University, and adhered to the ethical standards of the sixth revision of the Declaration of Helsinki. All participants gave their informed written consent to participate in the study.

3.2.2 Tasks and measures

3.2.2.1 Performance

A standard putter and a standard golf ball were used in the present study. Golf putts were performed on an artificial indoor putting green (size: 4 × 7 m). Participants performed putts to a target three meters away from the starting point. Specifically, participants were instructed to putt a golf ball as accurately as possible to the target, on which the ball was supposed to stop. The target was marked by a circle 10.8 cm (4.25 in) in diameter in accordance with the size of a regular golf hole. The outcome of each golf putt was recorded by capturing the final ball position after each putt with a motion capture system. Specifically, 6 T10 CCD cameras captured and tracked the golf ball rolling and stopping, with a spatial resolution of approximately 0.25 mm and a temporal resolution of 200 Hz.

3.2.2.2 Mental representation structure

In order to assess mental representation structure, we employed structural dimensional analysis of mental representation (SDA-M). This method provides psychometric data on the structure and dimension of mental representations of complex movements in long-term memory. More specifically, the SDA-M proceeds in four steps: (1) a split procedure delivering a distance scaling between the BACs of a suitably predetermined set, (2) a hierarchical cluster analysis used to outline the structure of the given set of BACs, (3) a factor analysis revealing the dimensions in this structured set of BACs, and (4) an analysis of invariance within- and between-groups in order to compare different cluster solutions (for details, see Schack, 2012). More specifically, in order to determine distances between BACs in memory, mental representation structure was assessed by way of a splitting task, first step of the SDA-M described above. The splitting task operates as follows: one BAC of the putt is permanently displayed on a computer screen (i.e., the anchor concept), while the rest of the concepts are presented one after another in randomized order. Participants are instructed to indicate whether a given BAC is related to the anchor concept or not during movement execution. As soon as a list of BACs is finished, another BAC takes the anchor position and the procedure continues. The splitting task is completed after each BAC has been compared to the remaining BACs (n-1).

In order to examine the underlying representation structure of the putt, the BACs of the movement have been adopted from Frank et al. (2013). Accordingly, the following 16 BACs for the putt were used in the present study: (1) shoulders parallel to target line, (2) align club face square to target line, (3) grip check, (4) look to the hole,

(5) rotate shoulders away from the ball, (6) keep arms-shoulder triangle, (7) smooth transition, (8) rotate shoulders towards the ball, (9) accelerate club, (10) impact with the ball, (11) club face square to target line at impact, (12) follow-through, (13) rotate shoulders through the ball, (14) decelerate club, (15) direct clubhead to planned position, (16) look to the outcome. Each of these 16 BACs of the putt can be designated to one movement phase: preparation (BAC 1-4), backswing (BAC 5-7), forward swing (BAC 8-9), impact (10-13) and attenuation (BAC 14-16).

3.2.2.3 Imagery ability

Visual and kinesthetic imagery ability was measured using the revised version of the Movement Imagery Questionnaire (MIQ-R; Hall & Martin, 1997). Accordingly, participants were asked to perform, imagine and finally rate their imagery experience of a series of movements. More specifically, after having performed a given movement, participants were instructed to either “see” or “feel” the movement without actually performing it. Next, they were asked to rate the ease or difficulty of imagining the movement on a 7-point Likert scale. This procedure was repeated for four different movements, and for both visual and kinesthetic imagery, resulting in eight items.

3.2.2.4 Manipulation check

For the two groups involving mental practice in their practice regime, as suggested by Goginsky and Collins (1996), a post-experimental questionnaire was administered following each practice session in order to investigate whether participants performed the imagery as instructed. Specifically, participants of the mental practice groups were asked to describe the content of their imagery in detail. In addition, they had to indicate on 7-point Likert scales (1= *very difficult*, 7= *very easy*), how easy it was for them to follow the instructions in general, as well as how easy it was to “see” and how easy it was to “feel” the movement in particular. Also, participants were asked how often they used an external perspective and how often they used an internal perspective (7-point Likert scales; 1= *never*, 7= *always*) during their imagery. Furthermore, they were asked whether they had experienced any problems, and whether they had any previous experience with imagery.

3.2.3 Procedure

The present study consisted of a pre-test, an acquisition phase on three consecutive days, followed by a post-test and a retention-test 72 hours later (see Table 3.1).

Table 3.1

Design of the study including three test days and an acquisition phase

	Pre-test	Acquisition			Post-test	Retention-test
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 8
Combined practice group (n = 13)	SDA-M	Putting practice (executed and imagined putts)			SDA-M	SDA-M
	Putting task				Putting task	Putting task
Physical practice group (n = 13)	SDA-M	Putting practice (executed putts only)			SDA-M	SDA-M
	Putting task				Putting task	Putting task
Mental practice group (n = 13)	SDA-M	Putting practice (imagined putts only)			SDA-M	SDA-M
	Putting task				Putting task	Putting task
Control group (n = 13)	SDA-M	No putting practice (reading)			SDA-M	SDA-M
	Putting task				Putting task	Putting task

Note: SDA-M: structural dimensional analysis of mental representation; putting task on test days: 3 x 20 putts; putting practice during acquisition phase: 3 x 20 (imagined or/ and executed) putts per day (practice groups) or 20 min of reading per day (control group).

3.2.3.1 Pre-test

On the first day, each participant signed informed consent forms. In order to become familiar with the movement, each participant watched a video of a skilled golfer performing the putting task. An introduction to the splitting task by the experimenter followed (for details on the SDA-M, see chapter 3.2.2). Before completing the splitting task, each participant was presented a randomized list of the 16 BACs of the putt. In order to ensure comprehension of the concepts, the experimenter explained the meaning of each of the 16 BACs to the participant. Next, the participants read the instructions on how to complete the splitting task. Specifically, participants were asked to decide whether the presented BACs are related to one another or not during movement execution. Following, the participants completed the splitting task. This procedure served to determine their starting mental representation structure of the putt. In order to assess their starting performance level, each participant then performed three blocks of 20 putts each. They were instructed to putt a golf ball as accurately as possible to the target, on which the ball was supposed to stop. As a measure of imagery ability, each participant completed the MIQ-R.

3.2.3.2 Practice phase

The next three days, participants of each practice group performed three blocks of twenty putts each (either physically or mentally or a combination of both), while participants of the control group did not practice the putt at all.

Physical practice (PP) group. Physical practice consisted of three blocks of 20 actual putts on each day of the practice phase. Specifically, participants were instructed to putt as accurately as possible to the target, on which the ball was supposed to stop. No additional information (e.g., technical feedback) was given. The visible outcome of the putt (i.e., knowledge of result) was the only feedback available for the participants.

Mental practice (MP) group. Mental practice on each practice day was comprised of specific motor imagery (i.e., putting imagery). Participants in this group did not physically execute the putt during practice. The motor imagery consisted of three blocks of 20 imagined putts each with a short break between the blocks. More specifically, each participant was asked to take the starting position as if they were going to actually putt. That is, participants stood upright on the green with the putter in their hands and their eyes closed. Next, the imagery script was read out loud to each participant, both at the beginning and before each block. Predefined by the script, participants were asked to imagine both the putting movement as well as the ball rolling toward the target and stopping on the target. In order to control for as many aspects during imagery as possible and to optimize the efficacy of the imagery intervention, participants were further told to imagine from an internal perspective (i.e., imagery perspective), to incorporate all the senses in their imagery (i.e., imagery modality), and to try and imagine as clear and as vivid as possible (i.e., imagery vividness) (cf. Holmes & Collins, 2001). After the script was read, participants imagined repeatedly the putting movement on their own. In order to enable the experimenter to control for the intended number of putts, participants were asked to indicate when having finished one putt in their imagery by slightly raising their index finger. Following imagery, participants of the mental practice group filled out a postexperimental questionnaire.

Combined practice (mental and physical practice; CP) group. The combined practice consisted of three blocks of twenty putts on each day of the practice phase, with each block consisting of 10 imagined followed by 10 actual putts (for specific instructions for each of the two types of practice, see both the physical practice group and mental practice group descriptions).

No practice (control; NP) group. The control group neither imagined nor executed the putting movement during the practice phase. Instead, participants in the control group were asked to read about golf in general in “Dream on: one hack golfer’s challenge to break par in a year” (Richardson, 2011). The reading lasted for twenty minutes each day, which is approximately the time needed to imagine three blocks of 20 putts.

3.2.3.3 Post-test and retention-test

In order to determine their final mental representation structures of the putting movement, all participants completed the splitting task again, one day after acquisition phase as well as after a retention interval of three days. In addition, each participant performed three blocks of 20 putts once more to assess their final outcome performance for post- and retention-test.

3.2.4 Data analysis

3.2.4.1 Mental representation structure

The structure of mental representations was assessed by way of cluster analysis resulting in mean group dendrograms (for more details, see Schack, 2012). For all cluster analyses conducted, an alpha-level of $\alpha = .05$ was chosen, resulting in a critical value $d_{crit} = 3.41$. BACs linked above this critical value were considered irrelevant. That is, links between concepts above this value were considered not related, while concepts linked below this value were considered related and thus resulted in a cluster. In order to compare differences between cluster solutions, analyses of invariance were conducted (Lander, 1991, 1992; see Schack, 2012). Accordingly, cluster solutions are variant (i.e., differ), for $\lambda < .68$, while cluster solutions are invariant (i.e., do not differ) for $\lambda \geq .68$. Moreover, the Adjusted Rand Index (ARI; Rand, 1979; Santos & Embrechts, 2009) was used to further investigate the degree of similarity between mean group dendrograms and a reference dendrogram reflecting the different movement phases. The Adjusted Rand Index is an index of similarity, ranging on a scale from -1 to 1. As the value "-1" denotes that cluster solutions are different and the value "1" denotes that two cluster solutions are the same, indices between "-1" and "1" mark the degree of similarity between two cluster solutions.

3.2.4.2 Performance

Putting performance was measured by two outcome variables (i.e., accuracy and consistency) for each time of measurement. Specifically, accuracy and consistency were calculated using two-dimensional error scores based on the x and y coordinates of each putt with the center of the target being the origin of the axes (see Hancock et al., 1995). Accuracy was measured by mean radial error (MRE), defined as a subject's average distance each putt came to the center of the target in mm. Consistency was measured by bivariate variable error (BVE), analogous to variable error in one-dimensional analyses, and defined as the square root of a subject's k shots' mean squared distance from their centroids in mm. A subject's centroid is a positionally typical shot whose coordinates are given by the average x and average y value of a subject's shots in mm. Learning over time was analyzed by way of two separate one-way MANCOVAs on both the post-test scores and the retention-test scores of the two dependent variables MRE and BVE. Specifically, a one-way MANCOVA on post-test scores with group as a between-subjects factor and pre-test scores as a covariate was conducted in order to examine whether the groups differed in their performance after acquisition phase as a result of practice condition, thereby controlling for potential differences in their pre-test performance. Regarding retention, a one-way MANCOVA on retention-test scores with group as a between-subjects factor and pre-test scores as a covariate was performed in order to examine whether the groups differed in their level of performance after a three day period of no practice, while controlling for the level of performance at baseline. Next, separate one-way ANCOVAs were conducted for each of the dependent variables. As directional effects had been specified a priori (CP > PP > MP > NP), one-tailed pairwise comparisons based on estimated marginal means served as tests of significance. A Holm-Bonferroni correction was employed in order to account for the inflation of type I errors (Holm, 1979). Cohen's *d* was used as an estimate of effect size (Cohen, 1992).

3.2.4.3 Imagery ability

In order to compare imagery ability between groups, three separate one-way ANOVAs on overall imagery ability (i.e., both scales together) as well as on visual and kinesthetic imagery ability were conducted.

3.3 Results

3.3.1 Imagery ability

Overall, participants reported acceptable visual imagery ability ($M = 21.46$, $SD = 3.84$.; 5.37 per item) as well as acceptable kinesthetic imagery ability ($M = 19.77$, $SD = 4.47$.; 4.94 per item). Specifically, on average participants scored approximately 5 on both scales (i.e., *somewhat easy to see/feel*), which is considered as sufficient imagery ability for subsequent mental practice sessions (e.g., Smith & Collins, 2004; Smith, Wright, & Cantwell, 2008). In addition, one-way ANOVAs on imagery ability revealed no main effect of group, neither for overall imagery ability, $F(3,48) = .273$, $p = .845$, $\eta_p^2 = .017$, nor for visual imagery ability, $F(3,48) = .170$, $p = .916$, $\eta_p^2 = .011$, or kinesthetic imagery ability, $F(3,48) = .198$, $p = .897$, $\eta_p^2 = .012$, indicating that imagery ability was similar for each of the four groups.

3.3.2 Manipulation check

In order to ensure that participants of the mental and mental-physical combined practice group had performed the imagery as instructed, participants' manipulation check responses were analyzed. None of the participants had prior imagery experience. In addition, none of the participants reported any problems during imagery sessions. Relating to the content of imagery, each participant mentioned the putting movement as well as the ball rolling in their descriptions of imagery content. Furthermore, for imagery perspective, mean scores during practice phase were 6.40, *very often* (*SD* = .53) for internal perspective and 1.80, *almost never* (*SD* = .85) for external perspective, indicating that participants of the mental practice and the mental-physical combined practice group had adopted an internal perspective during imagery. For ease of visual and kinesthetic imagery, participants scored an average of 4.37, *neither easy nor difficult* (*SD* = 1.40) for visual imagery and 4.67, *somewhat easy to feel* (*SD* = 1.49) for kinesthetic imagery, meaning that they had been able to "see" and to "feel" the movement while imagining. For instructions in general, mean scores were 4.73, *somewhat easy* (*SD* = 1.29), indicating that participants had been able to follow the instructions during imagery. Thus, participants had been able to perform the imagery as instructed, which was considered a prerequisite for subsequent data analyses.

3.3.3 Mental representation structure

While cluster analysis revealed little to no clustering in the mean group dendrograms of each group for pre-test, each practice group's dendrograms revealed changes over time (see Figures 3.1-3.3).

Mental practice group. While no distinct structure existed for the mental practice group at pre-test, a more elaborate mental representation structure was evident

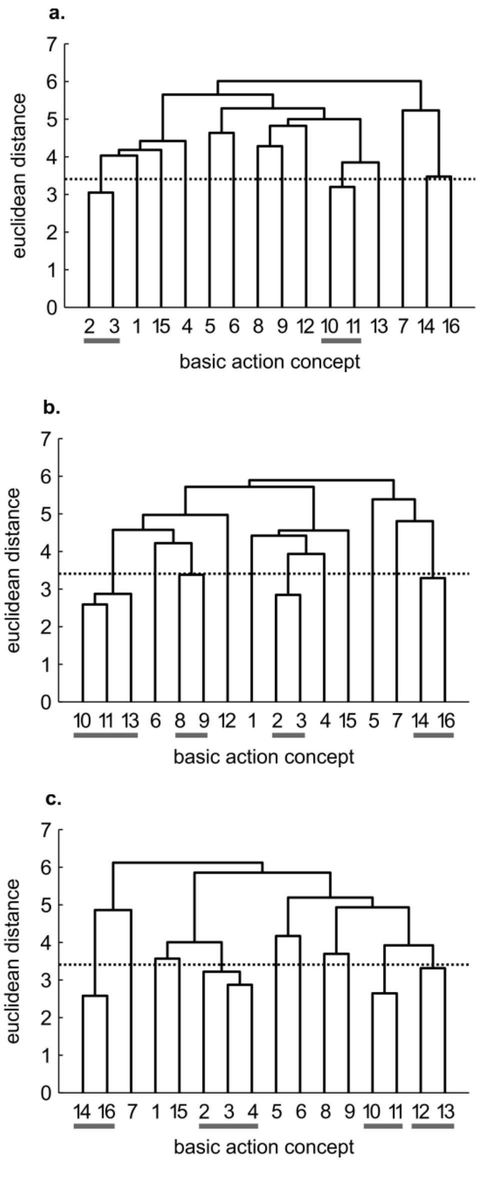


Figure 3.1. Mean group dendrograms of the mental practice group (n = 13) for the golf putt. The dendrograms refer to (a) pre-test, (b) post-test and (c) retention-test. The numbers on the x-axis relate to the BAC number, the numbers on the y-axis display Euclidean distances. The lower the link between related BACs, the lower is the Euclidean distance. The horizontal dotted line marks d_{crit} for a given α-level ($d_{crit} = 3.41$; α = .05): links between BACs above this line are considered not related; horizontal grey lines on the bottom mark clusters. BACs: (1) shoulders parallel to target line, (2) align club face square to target line, (3) grip check, (4) look to the hole, (5) rotate shoulders away from the ball, (6) keep arms-shoulder triangle, (7) smooth transition, (8) rotate shoulders towards the ball, (9) accelerate club, (10) impact with the ball, (11) club face square to target line at impact, (12) follow-through, (13) rotate shoulders through the ball, (14) decelerate club, (15) direct clubhead to planned position, and (16) look to the outcome.

after acquisition phase (see Figure 3.1). More specifically, four functional clusters were observed in the mental practice group's mean dendrogram at post-test, pertaining to three phases of the putt: preparation (i.e., BAC 2, 3), forward swing and impact (i.e., BAC 8, 9 as well as BAC 10, 11, 13), and attenuation (i.e., BAC 14, 16). The same was true for retention-test with some minor differences for impact phase (i.e., two separate clusters: BAC 10, 11 as well as 12, 13). Thus, for the mental practice group, an increase in the number of functional clusters was apparent in their mental representation structure over the course of the study. Statistical analyses of invariance confirmed the above presented descriptive results, revealing significant differences in representation structure between pre- and post-test, pre- and retention-test, as well as between post- and retention-test ($\lambda < .68$). What is more, increasing adjusted rand indices from pre-test (ARI = .17) to post-test (ARI = .44) and to retention-test (ARI = .44) indicated that, over the course of mental practice, the mean dendrograms of the mental practice group became more similar to the reference dendrogram (for an overview of ARIs, see Table 3.2). Hence, the changes in representation structure of the mental practice group are functional, and reflect a development towards an optimal structure.

Combined practice group. Similar to the mental practice group, the mental representation structure of the combined practice group was more elaborate after acquisition phase (see Figure 3.2). Again, four functional clusters were evident in the combined practice group's mean dendrogram at post-test, pertaining to preparation (i.e., BAC 2, 3), forward swing and impact phase (i.e., BAC 8, 9 as well as BAC 10, 11), and attenuation (i.e., BAC 14, 16). For retention-test, the mean group dendrogram revealed basically the same structure with some minor differences in the preparation (i.e., comprised of one additional concept: BAC 2, 3, 4) and the forward swing and impact phase (i.e., BAC 8, 9 and BAC 10, 11, 13). Hence, for the combined practice group, the number of functional clusters increased as well over the course of the study. Statistical analyses of invariance indicated significant differences in representation structure between pre- and post-test, pre- and retention-test, as well as between post- and retention-test ($\lambda < .68$). When being compared to the reference structure,

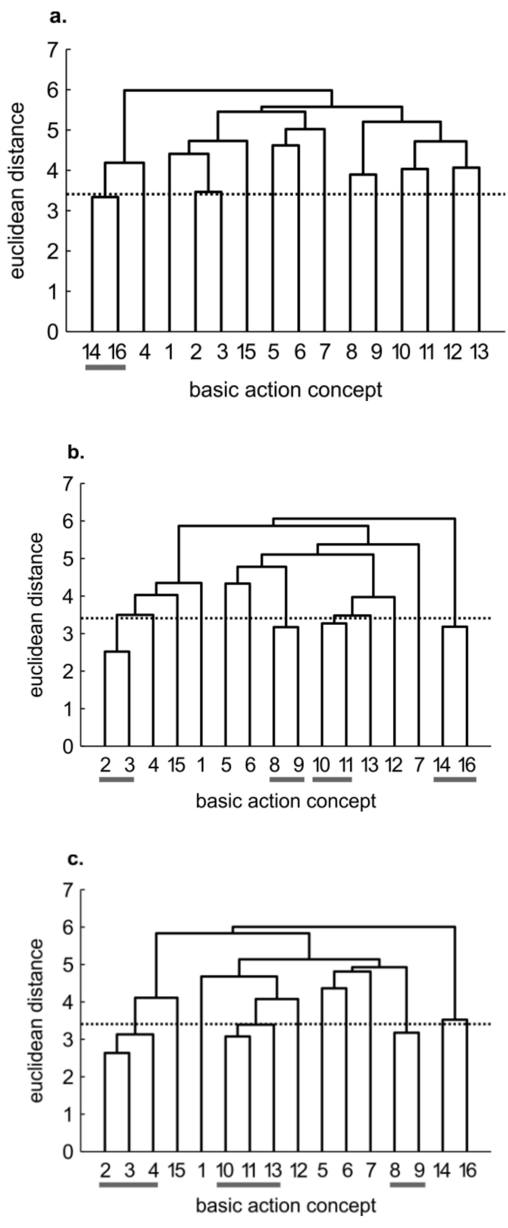


Figure 3.2. Mean group dendrograms of the combined practice group (n = 13) for the golf putt. The dendrograms refer to (a) pre-test, (b) post-test and (c) retention-test (α = .05; d_{crit} = 3.41).

increasing adjusted rand indices from pre-test (ARI = .09) to post-test (ARI = .31) and retention-test (ARI = .50) were evident, confirming that the mental representation structure of the combined practice group developed towards the reference structure over the course of the study.

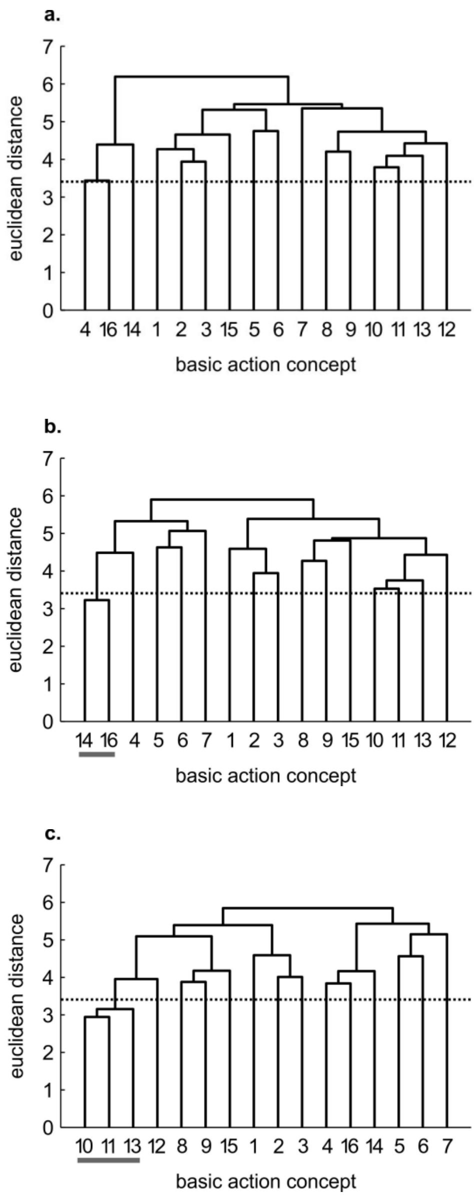


Figure 3.3. Mean group dendrograms of the physical practice group (n = 13) for the golf putt. The dendrograms refer to (a) pre-test, (b) post-test and (c) retention-test (α = .05; d_{crit} = 3.41).

Physical practice group. In contrast to the mental and the mental-physical combined practice groups, only minor changes in the mental representation structure of the putt were evident for the physical practice group (see Figure 3.3). Specifically, while the mean group dendrogram of the practice group revealed no cluster at pre-test, the dendrograms revealed one cluster for post-test (i.e., attenuation: BAC 14, 16). For retention-test, one meaningful cluster pertaining to the impact phase (i.e., BAC 10, 11, 13) was evident. Statistical analyses of invariance revealed significant differences between pre- and post-test, pre- and retention-test, as well as between post- and retention-test ($\lambda < .68$). Interestingly, the practice group's structure revealed only small changes toward the reference structure, with ARI increasing from pre-test (ARI = 0) to post-test (ARI = .09), and to retention-test (ARI = .24).

Control group. For the control group, changes in mental representation structure were small (see Figure 3.4). Specifically, while there were no clusters evident at pre-test, the control group's dendrogram revealed one cluster pertaining to aspects of attenuation of the putting stroke (i.e., BAC 14, 16) at post-test. After the retention interval, the mean dendrogram additionally revealed a second cluster reflecting parts of the preparation (i.e., BAC 2, 3). Statistical analyses of invariance indicated significant differences in representation structure between pre- and post-test, between pre- and retention-test, as well as between post- and retention-test ($\lambda < .68$). Furthermore, in comparison to the reference structure, the control group's structure showed only a slight trend towards that structure over time, with ARI increasing from pre-test (ARI = 0), to post-test (ARI = .08), and to retention-test (ARI = .17).

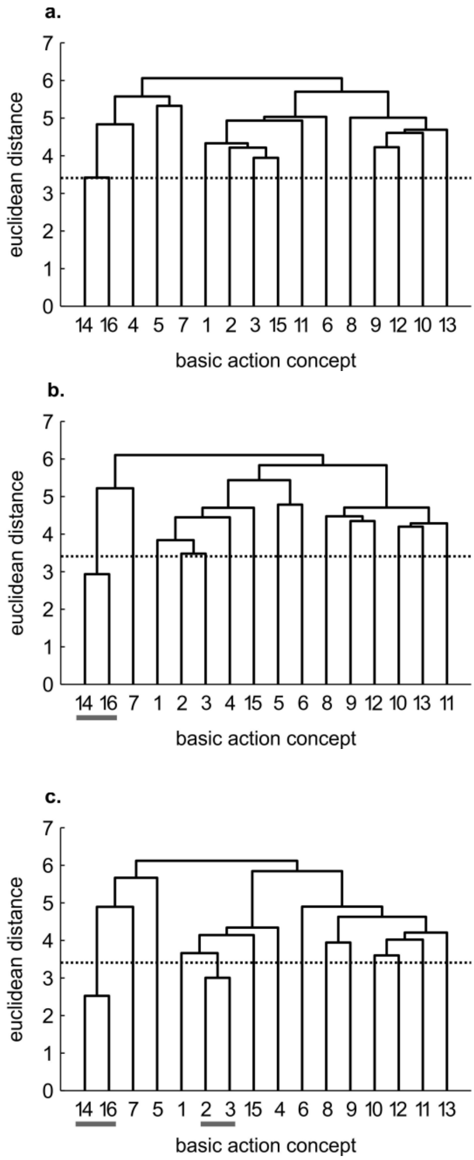


Figure 3.4. Mean group dendrograms of the control group (n = 13) for the golf putt. The dendrograms refer to (a) pre-test, (b) post-test and (c) retention-test (α = .05; d_{crit} = 3.41).

Table 3.2

Degrees of change in adjusted rand indices over the course of the study

	Degree of change in adjusted rand indices		
	Pre- to post-test	Pre- to retention-test	Post- to retention-test
Combined practice group (*n* = 13)	.22	.41	.19
Mental practice group (*n* = 13)	.27	.27	.00
Physical practice group (*n* = 13)	.09	.25	.15
No practice group (*n* = 13)	.08	.17	.09

Note: The adjusted rand index serves as an index of similarity on a scale from -1 to 1. On this scale, the value "-1" indicates that two cluster solutions (here: mean group dendrograms and the reference) are different and the value "1" indicates that two cluster solutions are the same. Indices between these extremes rank similarity between two cluster solutions.

Thus, each group's mental representation changed over the course of practice. Moreover, each group's structure developed to some extent in direction of the reference structure. More importantly, whereas the control and the physical practice groups' mental representations elicited only minor changes over the course of the study and showed only a small development towards the reference structure, the representation structures of the mental and the mental-physical combined practice group changed more, and approached more so an optimal representation.

3.3.4 Outcome performance

For the four groups, putting performance from pre-, to post- and to retention-test is displayed in Figures 3.5 and 3.6. As seen in Figure 3.5 and 3.6, the physical and the mental-physical combined practice groups performed more accurately and consistently after the acquisition phase, followed by the mental practice group, whereas the control group performed worst. After a three day retention interval, however, the mental-physical combined practice group performed with the greatest accuracy and consistency followed by the physical and the mental practice groups, while the control group again performed worst (see Figure 3.5 and 3.6).

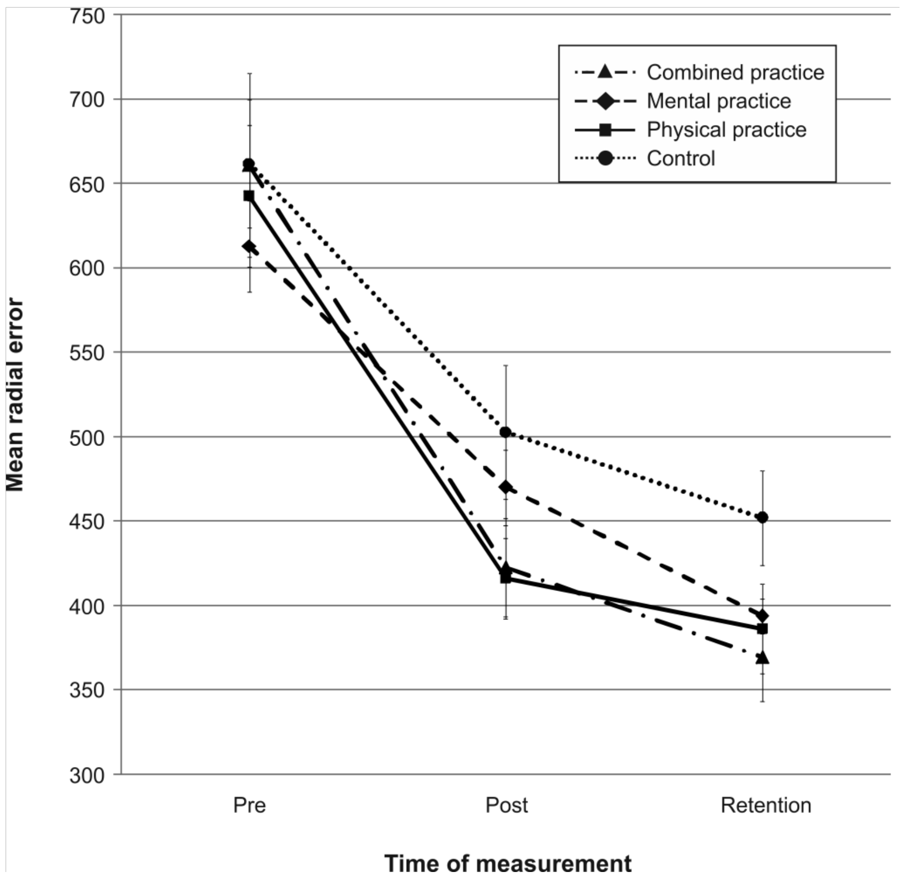


Figure 3.5. Putting accuracy. Mean radial error (i.e., accuracy) in mm from pre-test to post- and retention-test. The different lines relate to the different groups. Error bars represent standard errors.

Regarding the acquisition phase, a one-way MANCOVA on post-test scores of MRE and BVE revealed a significant main effect of *group*, Wilks' Lambda = .750, $F(6,90) = 2.326$, $p = .037$, $\eta_p^2 = .133$, 1-β = .784. Subsequent one-way ANCOVAs revealed a main effect of *group* for MRE, $F(3,46) = 3.218$, $p = .031$, $\eta_p^2 = .173$, 1-β = .704 as well as for BVE, $F(3,46) = 3.416$, $p = .025$, $\eta_p^2 = .182$, 1-β = .733. For MRE, pairwise comparisons incorporating a Holm-Bonferroni correction revealed no significant differences among the groups. For BVE, pairwise comparisons revealed that the combined practice group performed with more consistency compared to both the mental practice group (p = .005; α_{crit} = .008) and the control group (p = .009; α_{crit} = .010) post practice. The physical practice group, however, did not perform significantly different compared to either the mental practice group (p = .032; α_{crit} =.013), or the control group (p = .052; α_{crit} = .017). Regarding retention, a one-way MANCOVA on retention-test scores of MRE and BVE revealed no significant main effect of *group*, Wilks' Lambda = .849, $F(6,90) = 1.279$, p = .275, η_p^2 = .079, 1-β = .479.

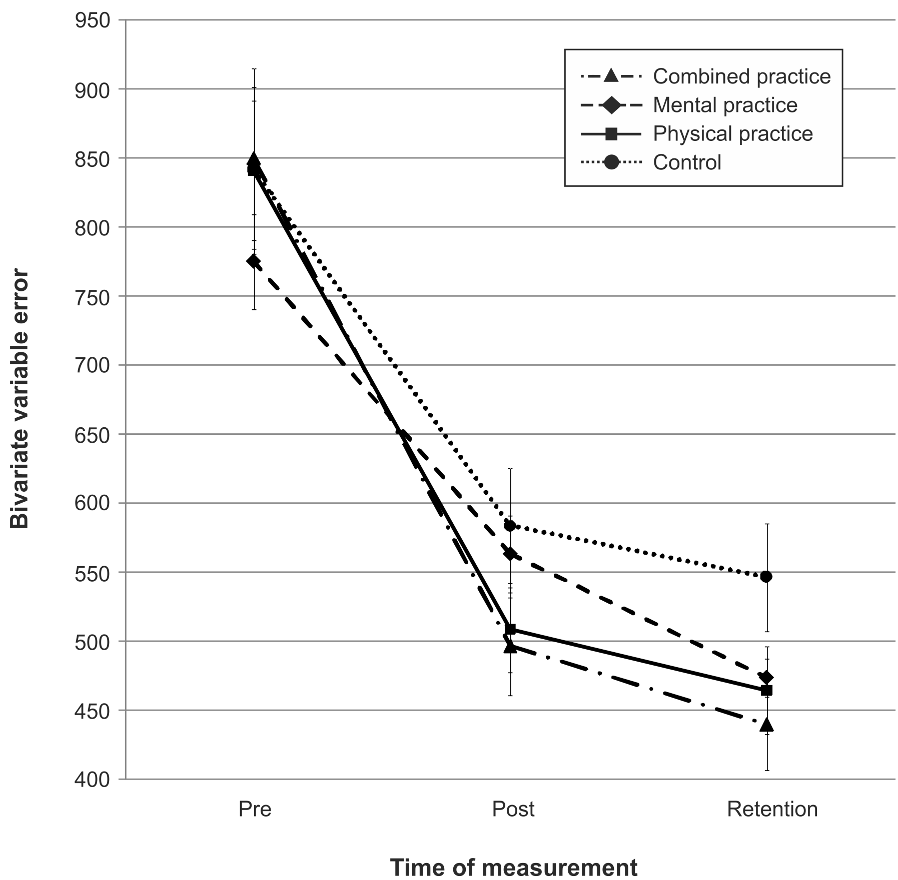


Figure 3.6. Putting consistency. Bivariate variable error (i.e., consistency) in mm from pre-test to post- and retention-test. The different lines relate to the different groups. Error bars represent standard errors.

Taken together, although the groups did not show differences in learning in terms of putting accuracy, clear differences were observed in terms of putting consistency such that the combined practice led to more consistent putting compared to both mental practice only and no practice. However, these differences between groups did not persist over the three day retention interval.

3.4 Discussion

In the present study, we investigated the effect of three different types of practice (mental practice, physical practice and their combination) in comparison to a no practice control group on both the performance and the mental representation structure of a complex movement during early skill acquisition. Overall, findings clearly denote order formation of basic action concepts of the putt together with improvements in putting performance. Interestingly, both types of practice involving imagery rehearsal (i.e., mental practice and combined practice) led to more structured and more elaborate representations, compared to physical practice and no practice.

While the mental representation structure of the control group and the physical practice group changed only marginally over time, the representation structure of the mental practice and the combined practice group elicited distinct changes over practice. Both after acquisition and after a retention interval of three days, the dendrograms of the mental practice as well as the combined practice group revealed four meaningful cluster, pertaining to functional aspects of the movement, and assignable to three movement phases in a golf putt (i.e., preparation, forward swing and impact, attenuation). Furthermore, changes in representation structures reflected a development towards a reference structure as indicated by increases in adjusted rand indices from pre-, to post-, and to retention-test. In contrast, the dendrograms of the control and the physical practice group revealed only minor changes over time. While for both groups one cluster relating to attenuation was evident after acquisition, the two dendrograms differed after a retention interval of three days. Specifically, the control groups mean dendrogram reflected two clusters pertaining to the beginning and the end of the movement (i.e., preparation and attenuation), whereas the physical practice group's dendrogram consisted of a cluster pertaining to the main phase of the movement (i.e., forward swing and impact). However, the small increases in adjusted rand indices from pre-, to post-, and to retention-test reflect only minimal development towards the reference representation. Thus, the mental and mental-physical combined practice led to more elaborate representation structures, more closely resembling an optimal representation, compared to the physical and no practice.

The results of the present study extend research on mental representations of complex action. Early research in this field, relating mental representation structure and skill level, has shown that high skill-level is associated with high order formation, and that low skill-level is associated with low order formation in long-term memory (e.g., Schack & Mechsner, 2006). Recently, Frank et al. (2013) demonstrated that practice leads to functional adaptations in one's mental representation of a complex action. Employing a similar design, the present study both replicates and extends findings reported by Frank et al. (2013). Similar to the study of Frank et al. (2013), mental representation structure were found to develop over the course of practice. More importantly, however, the present study extends findings obtained by Frank et al. (2013) by showing that mental practice adds to the adaptation process leading to even more elaborate mental representations compared to physical practice alone. Specifically, mental practice as well as combined mental-physical practice led to more structured representations than physical practice only and no practice. More specifically, mental representations of the putt were more similar to the reference structure for the practice groups involving mental practice of the skill than for the groups involving either physical practice only or no practice of the skill. From this, mental practice seems to lead to more developed mental representations than physical practice during early skill acquisition.

Interestingly, the mental representations of the four groups revealed slightly different patterns prior to the acquisition phase (see Figures 3.1a, 3.2a, 3.3a, 3.4a). To what extent this might influence the rate of representation development is unclear. To date, no research has examined whether the rate of development is influenced by the degree of structure in one's initial mental representation. In other words, it is conceivable that more or less structured initial representations may relate to the speed at which the structures change over the course of a practice interval. Consequently, future research is needed to clarify this point and help shed light on the learning process.

With respect to outcome performance, the combined practice led to more consistent putting performance over the course of learning compared to both mental practice only and no practice in the present study. This is in line with findings from previous research suggesting that a combination of physical and mental practice is most effective for the learning of a new motor skill (e.g., Hall et al., 1992). While the degree to which the groups learned during skill acquisition was influenced by practice type in the present study, these differences did not persist over the course of three days of no practice. Similar to other studies investigating the effect of mental practice on the retention of a motor skill (e.g., Spittle & Kremer, 2010), the groups did not differ in their retention performance of the acquired putting skill over the course of the retention interval.

While differences in putting consistency according to practice type were obvious after acquisition phase, no differences were found in putting accuracy in the present study. That is, participants differed in how consistent their putting was, but not in how accurate each putt came to the target. Moreover, physical practice did not significantly differ from either mental or no practice, neither in terms of accuracy nor in terms of consistency. Two main reasons may have caused the lack of differences during acquisition phase. First, as reflected by the minor changes in mental representation structure, participants in the control group seem to have learned from test trials. Thus, increases in putting performance for the control group may be due to repeatedly executing the putt during test days. Second, the lack of differences may also be due to the relative short length of the study. Specifically, too few practice sessions during acquisition phase may have resulted in the lack of clear differences between the groups. This may also be a reason for the finding that the four groups did not differ in their ability to retain their level of putting skill over three days of no practice. It is likely that larger differences would emerge over a greater length of practice. Future studies, therefore, should consider utilizing fewer trials during test days and more practice sessions during the acquisition phase to prevent this possible confound.

Whereas the groups involving physical practice (i.e., PP + CP) elicited the best putting performance after practice, those groups practicing mentally (i.e., MP + CP) revealed more elaborate representation structures after practice compared to groups who did not practice mentally. These differences pertain to distinct mechanisms underlying mental practice and physical practice. In other words, each of the groups may have learned in different ways. Learning induced by mental practice may primarily operate through and find expression on the cognitive level, whereas learning via physical practice may primarily operate through and find expression on the motor output level. In this light, it seems plausible that the two groups involving mental practice elicited more developed mental representations than the groups not practicing mentally. To explain, mental practice can be considered an "offline" process requiring primarily the re-creation of an experience from memory while covertly imagining a movement (cf. distinction between online task performance (i.e., real-time skill execution) and offline task performance (i.e., no real-time skill execution, no overt act); cf. Beilock & Lyons, 2009). As there is no online information available during imagery, this process is thought to rely on memorial information only (Farah, 1984). Thus, we propose that mental practice may work via the structuring of memorial information (i.e., the structuring of mental representation), and as such causes adaptation processes within the motor action system. In contrast, physical practice, being an online process, requires the online integration of perceptual feedback during overt movement execution, and therefore does not primarily rely on the offline reconstruction of an experience from memory. Accordingly, physical practice applies via the integration of sensory information and as such promotes adaptation processes in this manner. Taken together, we propose that, while physical practice causes feedback-induced online adaptation, mental practice may cause memory-induced offline adaptation. In this regard, the memory-induced offline adaptation may have led to a cognitive structuring advantage in the sense of more structured memorial information on the movement (i.e., more developed mental representations of the putt) in the two groups that involved mental practice.

It seems quite interesting that, whereas mental and mental-physical combined practice led to more elaborate representation structures compared to physical and no practice, this difference was not fully expressed on the performance level in the present study. Specifically, although the findings of the present study point to the idea that mental practice in early skill acquisition may help to structure mental representation more than physical practice, this cognitive structuring advantage itself does not seem to transfer one-to-one to the motor output level. Being an “offline” process, this cognitive structuring itself seems to not immediately lead to better motor performance. It might be the case that this cognitive advantage does not turn into a performance advantage, unless online feedback is available and is being integrated. Accordingly, although the mental-physical combined practice group performed equally to physical practice in the present study, a closer look at the data points to the possibility that combined practice may be even superior to physical practice after a greater amount of practice. In fact, the combination of mental and physical practice has been suggested to be most effective in improving performance (e.g., Hall et al., 1992). In this sense, one might speculate that the controllability of the motor action system can best be achieved via both memory-induced offline adaptation (i.e., mental practice) and feedback-induced online adaptation (i.e., physical practice). Accordingly, future research might focus on long-term and transfer effects of mental and physical practice on both the performance and the representation of a motor skill.

What’s more, the findings of the present study fit well into the body of research on the cognitive-motor hypothesis (e.g., Smyth, 1975; Ryan & Simons, 1981, 1983; Wrisberg & Ragsdale, 1979), and even extend it as we will elaborate in the following. The cognitive-motor hypothesis states that mental practice is more effective in cognitive tasks compared to motor tasks. That is, while mental practice is suggested to be effective both for cognitive and motor tasks, this hypothesis differentiates such that cognitive tasks are suggested to benefit even more from mental practice compared to motor tasks. Thus, the more cognitive a task is, the more it might benefit from mental practice. Up to now, findings largely support this hypothesis: although mental practice has been found to be effective in motor tasks (e.g., Yue & Cole, 1992), effect sizes reported in the meta-analysis conducted by Driskell et al. (1994) were greater for cognitive tasks (d = .69) than for motor tasks (d = .34). To explain, the typical design of these studies examining the cognitive-motor hypotheses consists of two groups practicing mentally, each practicing a different task: one group practicing a cognitive task, and one group practicing a motor task. That is, two different tasks (i.e., one motor and one cognitive task) are employed in order to examine the influence of mental practice on resulting performance (e.g., Ryan & Simons, 1981, 1983). However, to our knowledge, no study has been conducted so far that takes into account both the cognitive and the motor level within one task. Thus, no statements can be made so far whether mental practice affects more the cognitive compared to the motor level within a motor task. In the present study, we employed one task (i.e., golf putting) and examined the effect of mental practice on two different variables, one "cognitive" variable (i.e., mental representation structure) and one "motor" variable (i.e., putting performance). Thus, we used a within-task design, taking into account both the cognitive and the motor level of the golf putt. If we related the research question of the present study back to the cognitive-motor hypothesis, one would expect that mental practice would affect the cognitive structures to a larger degree than the motor output of a motor task. That is exactly what we found in the present study.

It seems important to note that oftentimes in mental practice studies, a potential lack of differences in performance according to practice type results in conclusions such that mental practice is not effective in novices. This is, of course, true with respect to performance. However, these studies do not take into account covert processes. Yet, according to learning theories, proposing that first stages of learning are primarily cognitive in nature, one might expect that changes evoked by mental practice (i.e., a cognitive type of practice) primarily take place on the cognitive level in early skill acquisition, and that these changes may not be transferred one-to-one on to the motor level without additional physical practice (i.e., a motor type of practice during which the performer repeatedly receives actual perceptual feedback).

Accordingly, one would expect mental practice to especially affect the development of these cognitive processes. For the host of studies reporting no differences according to practice type, this would not necessarily mean that there were no differences between groups, but perhaps that the variables that may elicit these differences had not been measured. With the present study, we were able to show that, although not obvious from overtly observable putting performance, mental practice covertly helped to develop mental representation structure in novices.

In sum, the results of the present study clearly demonstrate that practice leads to functional adaptations in the representation structure of complex action, and that mental practice supports this adaptation, leading to even more elaborate representations. While research in the field of mental practice has largely focused on overtly observable performance effects during early skill acquisition, thereby mostly neglecting the investigation of covert cognitive effects, we showed that repeatedly imagining a movement affects the development of one's underlying mental representation structure. Building on these findings, it would be of interest to learn more about the adaptation of mental representation structure on the way to expertise. From a theoretical point of view, future research might focus on the question how different (mental) practice conditions (e.g., duration, scheduling, composition of practice) contribute to the development of mental representation structure, and, even more importantly, what conditions are most effective in contributing to the formation of an expert structure. From an applied point of view, a valuable future objective would be to examine whether practice and mental practice tailored to the one's current skill representation (i.e., individualized physical and mental practice; e.g., Schack, Essig, Frank, & Koester, 2014) is more effective than standard type of practice not considering one's cognitive prerequisites. To conclude, during early phases of skill acquisition, motor learning is associated with order formation of action-related knowledge in long-term memory, and this order formation seems to be promoted by mental practice.

4 MENTAL AND PHYSICAL PRACTICE, THE DEVELOPMENT OF MENTAL REPRESENTATION STRUCTURE AND GAZE BEHAVIOR

This chapter is based on the manuscript

Frank, C., Land, W. M., & Schack, T. (under review). Perceptual-cognitive changes during motor learning: The influence of mental and physical practice on mental representation, gaze behavior, and the performance of a complex action. *Psychological Research.*

Abstract

Despite the wealth of research on the learning of a motor action, little is known about the perceptual-cognitive background of motor learning. In the present study, the influence of mental and physical practice on putting performance, mental representation of the putt, and gaze behavior during the early stages of skill acquisition was examined. Novices (N = 45) were assigned to one of three conditions: combined mental and physical practice, physical practice, and no practice. Participants in the practice groups trained on a golf putting task over the course of three days either by repeatedly executing and imagining or by executing it. Putting performance was measured using error scores. Mental representations were assessed by way of structural dimensional analysis of mental representation providing psychometric data on the relation of action concepts in long-term memory. Gaze behavior was measured using eye-tracking. Dependent variables were measured prior to and post practice as well as after a retention interval. For combined practice, findings revealed both perceptual-cognitive changes (i.e., more elaborate representation structures and longer quiet eye durations) and changes in motor performance (i.e., better accuracy and consistency). In contrast, although putting performance improved with physical practice, neither any substantial changes in representation structures or longer quiet eye durations were evident. These findings suggest that the combination of mental and physical practice best promotes the covert perceptual-cognitive adaptation process within the motor action system during motor learning. In respect thereof, potential benefits of adopting a multilevel approach for examining the motor action system are discussed.

4.1 Introduction

Movement can be regarded as a product of the interplay between perceptual, cognitive, and motor processes. Consider, for instance, a highly-skilled golfer performing a golf putt toward a hole that is several meters away from her. She takes her time to read the green and to estimate the distance from the ball to the hole. Based on this information, she performs a putting stroke that is thought to hit the ball with the appropriate force in the appropriate direction in order to sink the putt. Success at such a task can be viewed as involving a perceptual-cognitive component (e.g., estimating and reading the green) and a motor component (e.g., performing the putting stroke). In fact, research has shown that experts do not only differ from novices in their reproducibly superior performance, but also in their gaze behavior (e.g., Campbell & Moran, 2014; Vickers, 1992; Williams, Singer, & Frehlich, 2002) as well as in their underlying skill representation (e.g., Ericsson, 2007; Ericsson & Smith, 1991; Hill, 2007; Schack & Mechsner, 2006). Both variables have been shown to mediate performance. From this it becomes evident that, on the way to skilled motor action, not only directly observable components of motor action change, but also the perceptual-cognitive components of the motor system develop.

According to perceptual-cognitive approaches to motor control and learning, motor actions are guided by way of representations holding information about the perceptual effects of the actions (e.g., theory of anticipative behavioral control: Hoffmann, 1993; theory of event coding: Hommel, Müsseler, Aschersleben, & Prinz, 2001). In this sense, actions are primarily guided by cognitively represented effects. To explain, as the individual acts in her environment in order to attain a particular goal (e.g., to sink a putt), she perceives the effects of her action (e.g., the putt was too long). These perceived and cognitively represented effects, in turn, serve as an essential control variable to guide her future motor action. In this sense, perceptual-cognitive approaches to motor action assume a close functional relationship between motor action and the corresponding, cognitively represented perceptual effects (for an overview, see e.g., Mechsner, 2004; Nattkemper & Ziessler, 2004). Skilled action, in this sense, relies on well-developed effect representations, and motor learning, accordingly, is associated with the constitution and the refinement of effect representations.

One such perceptual-cognitive approach, arising in the tradition of Bernstein (for more details, see Schack, 2004; Bernstein, 1947, 1967, 1996), and being situated at the interface of cognitive psychology and movement science, is the cognitive action architecture approach (CAA-A; for an overview, see Schack, 2004; Schack & Mechsner, 2006). According to this approach, motor actions are represented in memory as well-integrated representational networks comprised of basic action concepts (BACs). Analogous to object representations and the idea of basic object concepts (e.g., Hoffmann, 1986, 1990; Mervis & Rosch, 1981; Rosch, 1978; Rosch & Mervis, 1975), the BACs represent cognitive compilations of movement elements, body postures, and their corresponding perceptual effects that are closely tied to the attainment of action goals (e.g., Schack, 2004; Schack, 2012). For instance, grip check as a BAC of the golf putt is a cognitive chunk serving a particular action goal (i.e., to ensure an optimal grip during the preparation of the putting movement before initiation of the backswing). As such it is comprised of the corresponding body posture (e.g. standing up right, hips flexed, upper body leaning forward, holding the putter in hands) and movement elements (e.g., take grip, move fingers until in right position) together with their sensory consequences (e.g., feel hands touching the surface of club; sense slight pressure in fingers, see both hands touch each other). As such, these representational networks comprised of BACs allow controlling the motor system during motor action. Consequently, motor learning, according to the CAA-A, is associated with the modification of representational networks of the action to be learnt (e.g., Schack, 2004; Schack & Ritter, 2013).

The most common means to acquire a motor skill and to induce persisting improvements in performance is through physical practice, mental practice, or both. While physical practice involves the repeated overt execution of the movement to be learned, mental practice in the form of motor imagery rehearsal relates to the covert repeated simulation of a movement in one’s mind without subsequent movement execution (e.g., Jeannerod, 2004; Moran, Guillot, MacIntyre, & Collet, 2012). Both types of practice have shown to influence performance and to promote motor learning (e.g., Driskell et al., 1994; Feltz & Landers, 1983; Feltz et al., 1988; Grouios, 1992; Hinshaw, 1991). By comparing the effect of these two types of practice on motor performance, meta-analyses have reported strong effect sizes for physical practice and moderate effect sizes for mental practice (e.g., Driskell et al., 1994) in comparison to no practice. Furthermore, various studies examining the effect of a combination of mental and physical practice have found combined practice to be the most effective practice type (for an overview, see Hall et al., 1992). From this, three main conclusions with respect to motor performance have been drawn: (1) physical practice is superior to mental practice, (2) mental practice is better than no practice, and (3) a combination of mental and physical practice is most effective in improving performance and thus in promoting learning of motor actions.

Despite the wealth of research on the influence that mental and physical practice have on the performance of a motor action, the perceptual-cognitive components of motor action, and the perceptual-cognitive changes associated with motor learning, respectively, are less clear. Regarding underlying mental representations of motor actions, both mental and physical practice have shown to influence the development of mental representations (Frank et al., 2013; Frank, Land, Popp, & Schack, 2014; Land et al., 2014). During motor learning, the mental representation of a motor action functionally adapts in the direction of an elaborate representation, thereby relating more so to the biomechanical task demands. Specifically, Frank et al. (2013) investigated the changes in skill representation during motor learning. The authors found that skill representation of novices practicing (i.e., repeatedly executing without technical instructions) a golf putting task for several days changed over the course of practice such that the novices' representations developed in the direction of that of an expert. More specifically, novices' unstructured representations became more structured over time, with the groupings of BACs pertaining to the movement phases of the putt (i.e., the preparation, the forward swing and the impact). In contrast, novices who did not practice the putt revealed no changes in their underlying representation structure, and thus their representation remained unstructured.

In a more recent study, the adaptation of mental representation according to type of practice was investigated (Frank et al., 2014). Novices practiced the golf putt under one of four conditions: mental practice, physical practice, combined mental and physical practice, and no practice. Both putting performance and mental representation of the putt were assessed prior to and after three days of practice, and again after a 72 hour retention period. While the putting performance of the groups reflected improvements as expected (i.e., the combined practice group performing best, followed by the physical practice group, while the mental practice group performed worst after practice), mental representations developed differently between the groups. While the physical practice group showed only marginal changes in representation structure over time, both the mental practice and the combined practice group revealed major changes in their representations of the putt after the acquisition phase. That is, after mental practice and after combined mental and physical practice, the trained novices elicited elaborate representation structures, reflecting the functional phases of the movement (i.e., the preparation phase, the swing and the impact phase, and the attenuation phase). Thus, representation structures seem to develop differently during motor learning, depending on the type of practice. To this extent, mental practice facilitates the functional adaptation of skill representation (i.e., the cognitive adaptation; for a detailed discussion, see Frank et al., 2014) during skill acquisition. From these findings, motor learning is associated with improvements in motor performance along with the refinement of underlying representational structures of the task. These skill representations are vital to the perceptual-cognitive component of skill execution by allowing skilled performers to better encode, process, store, and retrieve movement-related information.

A further important factor associated with the perceptual-cognitive component of motor performance is gaze behavior. One can distinguish between several gaze strategies: saccades, fixations, and pursuit tracking. In sports, much attention has been directed towards a specific type of gaze, the quiet eye. According to Vickers (2009, p.

280), the quiet eye is defined as "the final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace within 3° of visual angle for a minimum of 100 ms. The onset of the quiet eye occurs prior to the final movement in the task and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms (…)", and is thought to be an indicator of information processing prior to movement onset. Specifically, the quiet eye period has been suggested to be the period of time during which the environmental information the performer attends to is being processed cognitively. More specifically, visual input is being processed in order to prepare an adequate motor response. Thus, the quiet eye phenomenon is suggested to reflect the time necessary for optimal motor programming prior to the onset of the movement.

The quite eye has been found in various tasks across various sports (for reviews, see Vickers, 2007, 2009), including golf (e.g., Vickers, 1992). To date, research has elicited distinct differences in this type of gaze behavior between skilled and non-skilled performers. Compared to non-skilled performers, the quiet eye duration of skilled performers is longer (e.g., Janelle, Hillman, Apparies, Murray, Meili, Fallon, & Hatfield, 2000; Vickers, 1992, 1996; Williams et al., 2002). Moreover, skilled performers have been shown to perform with an optimal duration of the quiet eye depending on the type of task (Vickers, 2007; Williams et al., 2002). In the specific case of golf putting, experts' quiet eye period lasted in between 2 and 3 seconds, while non-experts' quiet eye durations lasted around 1.5 seconds (Vickers, 1992; Vickers, 2007). Furthermore, performance has been shown to be directly related to quiet eye duration. For example, longer quiet eye periods have been reported for successful putts compared to unsuccessful putts (Wilson & Pearcy, 2009). In fact, the quiet eye has been found to be a major factor related to perceptual-cognitive expertise, differentiating between experts and non-experts (Mann, Williams, Ward, & Janelle, 2007). From this, it seems that skilled performance is accompanied by longer quiet eye durations, indicating more extensive information processing during motor preparation. While quiet eye duration has been repeatedly linked to skilled performance, to date, research has yet to investigate the change in quiet eye duration over the course of skill development, particularly as it relates to different modes of learning (e.g., mental and physical practice).

Taken together, while there has been a wealth of research on the influence of mental and physical practice on motor performance, the perceptual-cognitive background of performance changes induced by mental and physical practice is less clear. By investigating changes on both the motor output level as well as the perceptual-cognitive level, we hope to learn more about different types of practice and their relative influence on the motor system. Thus, the overall goal of the present study was to gain further insights into changes within the motor system during skill acquisition by investigating the perceptual-cognitive background of performance changes associated with learning a golf putting task. Specifically, the objective of the present study was to examine the influence of mental and physical practice on golf putting performance, mental representation of the golf putt, and quiet eye duration during golf putting. In line with previous research, we expect putting performance to improve as a result of practice, with putting accuracy and consistency being better after combined mental and physical practice (i.e., physical practice with additional mental practice) compared to physical practice only (i.e., physical practice without additional mental practice). Moreover, we expect mental representations to develop over the course of practice, with representation structures being more elaborate after combined practice compared to physical practice only. Specifically, we hypothesized that representations would be more similar to the mental representation of an expert golfer after combined practice compared to physical practice only. Of particular interest for the present study was the question whether, in addition to the development in mental representation structure, changes in quiet eye duration would be evident as a result of practice. As has been elaborated in more detail above, the duration of the quiet eye can be viewed as an indicator of the extent of pre-programming prior to movement execution. Since representations become more elaborate during motor skill acquisition, and since the pre-programming is heavily dependent on the representation available, more extensive information processing prior to movement onset may become evident based on more elaborate representations after practice. Thus, we expected quiet eye durations to become longer together with representations becoming more elaborate over the course of practice. Furthermore, we hypothesized that the quiet eye period would be associated with practice condition, with longer quiet eye durations after combined practice compared to physical practice only.

4.2 Methods

4.2.1 Participants

Forty-five students participated in the present study. None of the participants had any prior experience with golf putting. In order to ensure comparable performance levels at baseline between conditions, participants were assigned to one of three conditions according to their pre-test performance: combined mental and physical practice (n = 16, M_{age} = 24.38 years, SD = 2.73, 8 female), physical practice (n = 15, M_{age} = 25.73 years, SD = 2.99, 10 female) and no practice (n = 14, M_{age} = 27.00 years, SD = 8.74, 9 female). The study was conducted in accordance with local ethical guidelines, and conformed to the declaration of Helsinki.

4.2.2 Tasks and measures

4.2.2.1 Performance

Participants performed a golf putting task on an artificial indoor putting green (size: 4 × 9 m), using a standard putter and golf ball. The task consisted of putting the ball to a target three meters away from the starting point. The target, projected onto the surface of the green via an overhead projector, corresponded to the size of a regulation golf hole (i.e., 10.8 cm in diameter). Participants were asked to putt the golf ball as accurately as possible to the target, on which the ball was supposed to stop. Putting performance was recorded by way of a motion capture system. Specifically, 6 T10 CCD cameras captured and tracked the ball rolling and stopping. The recordings were made with a temporal resolution of 200 Hz and a spatial resolution of approximately 0.25 mm.

4.2.2.2 Mental representation structure

As described elsewhere in detail (Frank et al., 2013), structural dimensional analysis of mental representation (SDA-M) was employed to assess mental representation structures of the putt. By way of this method, it is possible to obtain psychometric data on the structuring and dimensioning of mental representations of complex movements in long-term memory. In other words, the SDA-M serves to determine relations between and the grouping of basic action concepts (i.e., BACs) of a motor action. For the specific purpose of the present study, 16 BACs for the putt were used (see Table 4.1; for more details, see also Frank et al., 2013), each pertaining to one particular movement phase: preparation (BAC 1-4), backswing (BAC 5-7), forward swing (BAC 8-9), impact (10-13), and attenuation (BAC 14-16).

The SDA-M consists of several steps. In a first step, a split procedure results in a distance scaling between the BACs of a predetermined set. Next, a hierarchical cluster analysis is used to outline the structure of the given set of BACs. Following this, a factor analysis can be used in order to determine the dimensions in the structured set of BACs. In a last step, an analysis of invariance within- and between-groups serves to compare different cluster solutions (for details, see Schack, 2012). More specifically, the splitting task (i.e., first step of the SDA-M) proceeds as follows: while one BAC of the putt is permanently shown on a computer screen (i.e., the anchor concept), the rest of the BACs are displayed one after another in randomized order. For each of the BACs being displayed together with the anchor concept, participants are asked to decide whether the given BAC is related to the anchor concept or not during movement execution. Once the participant has finished a list of BACs, another BAC takes the anchor position and the procedure continues. After each BAC has been compared to the remaining BACs (n-1), the splitting task is completed.

Table 4.1

Basic action concepts (BACs) of the golf putt

N°	Basic action concept (BAC)	Movement phase	Motor action
1	Shoulders parallel to target line	Preparation	Golf putt
2	Align club face square to target line		
3	Grip check		
4	Look to the hole		
5	Rotate shoulders away from the ball	Backswing	
6	Keep arms-shoulder triangle		
7	Smooth transition		
8	Rotate shoulders towards the ball	Forward swing	
9	Accelerate club		
10	Impact with the ball	Impact	
11	Club face square to target line at impact		
12	Follow-through		
13	Rotate shoulders through the ball		
14	Decelerate club	Attenuation	
15	Direct clubhead to planned position		
16	Look to the outcome		

Note: Each of the 16 basic action concepts (BACs) of the golf putt can be functionally assigned to one of the movement phases. The numbers on the left relate to the different BACs; they do not reflect a particular order, but serve to better display the concepts in Figures 3-5.

4.2.2.3 Gaze behavior

Gaze behavior was measured by way of eye-tracking while putting. Accordingly, eye-movements were recorded using a head-mounted portable eye-tracking system with an eye and a scene camera. Specifically, the SMI iViewX HED mobile eye-tracker is a corneal reflex system that operates monocular at a sampling rate of 200 Hz, with a gaze position accuracy < 0.5°-1°. Each recorded scene video had a resolution of 376 x 240 pixels at 25 fps (1 frame = 40 ms). This system allows for the recording of eye-movements in natural environments in which participants move and interact with their environment while performing complex movements (i.e., vision in action paradigm; see Vickers, 2007).

4.2.2.4 Imagery ability

To assess visual and kinesthetic imagery ability, the revised version of the Movement Imagery Questionnaire (MIQ-R; Hall & Martin, 1997) was administered. During this procedure, participants (a) perform, (b) imagine and (c) rate their imagery experience of four different movements. During the imagery, participants are instructed to either “see” or “feel” one of the four movements without actually performing. Following this, participants are asked to rate the ease or difficulty of imaging the movement on a 7-point Likert scale. Thus, participants imagine each of the four movements, by using both the visual modality and the kinesthetic modality separately by instruction, resulting in a final rating of eight items.

4.2.2.5 Manipulation check

In order to control whether participants performed the imagery as instructed (cf. Goginsky & Collins, 1996), a post-experimental questionnaire was administered after each practice session to those participants practicing mentally. Specifically, we asked participants of the combined mental and physical practice group to report their imagery in detail. First, participants were asked to describe the imagery content shorthand. Second, participants had to rate on a 7-point Likert scales (1 = *very difficult*, 7 = *very easy*; 1 = *never*, 7 = *always*), how easy it had been to follow the instructions in general, how often they used an external perspective and how often they used an internal perspective. Third, participants were asked to indicate how easy it had been to “see” and how easy it was to “feel” the putt during their imagery. Finally, after completion of the splitting task, we asked participants whether they had experienced any problems and, if so, to describe them in detail.

4.2.3 Procedure

The present study consisted of a pre-test, an acquisition phase of three consecutive days of practice, a post-test, and a retention-test after three days of rest (see Table 4.2).

Table 4.2

Design of the study including three test days and an acquisition phase of three days

	Pre-test	Acquisition			Post-test	Retention-test
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 8
Mental and physical practice group ($n = 16$)	Eye-tracking	Mental + physical practice *(imagined and executed putts)*			Eye-tracking	Eye-tracking
	Putting task				Putting task	Putting task
	SDA-M				SDA-M	SDA-M
Physical practice group ($n = 15$)	Eye-tracking	Physical practice *(executed putts only)*			Eye-tracking	Eye-tracking
	Putting task				Putting task	Putting task
	SDA-M				SDA-M	SDA-M
Control group ($n = 14$)	Eye-tracking	No practice *(neither executed nor imagined putts)*			Eye-tracking	Eye-tracking
	Putting task				Putting task	Putting task
	SDA-M				SDA-M	SDA-M

Note: SDA-M: structural dimensional analysis of mental representation; putting task on test days: 2 warm-up putts followed by 20 putts; putting practice during acquisition phase: 3 x 20 imagined and executed putts (combined mental and physical practice group) or 3 x 10 executed putts (physical practice group) per day for the practice groups.

4.2.3.1 Pre-test

At the beginning of the study, participants signed informed consent forms. Next, in order to become familiar with the task at hand, participants watched a video showing a skilled golfer performing the putting task. Following this, the eye-tracking system was calibrated, employing a standard five-point calibration procedure. In order to assess participants' initial putting performance and gaze behavior, each participant performed two warm-up putts followed by 20 putts. Participants were asked to putt a golf ball as accurately as possible to the target, on which the ball was supposed to stop. After the putting, an introduction to the splitting task was given. This procedure served to assess the participant's initial mental representation structure of the putt. Accordingly, in order to ensure comprehension of the concepts, a randomized list of the 16 BACs of the putt was presented and explained to the participants. After having read general instructions on how to complete the splitting task, participants were explicitly instructed to decide whether the presented basic action concepts were related to one another or not during movement execution. Finally, each participant completed the MIQ-R as an indicator of imagery ability.

4.2.3.2 Acquisition phase

During the next three days, participants either practiced the putt (practice groups), or did not partake in putting practice (control group).

Physical practice (PP) group. Three blocks of 10 putts were performed on each practice day in the physical practice condition. Prior to each block, participants were asked to putt as accurately as possible to the target, on which the ball was supposed to stop. Importantly, no other information than the visible outcome of the putt (i.e., knowledge of result) was available to the participants. That is, no additional information such as technical feedback (i.e., knowledge of performance) was given to the participants during the acquisition phase.

Combined mental and physical practice (CP) group. Three blocks of 20 putts were performed on each practice day in the combined mental and physical practice condition, with each block consisting of 10 imagined and 10 actual putts. Prior to each block, participants were asked to take the starting position. While participants were standing upright on the green with the putter in their hands, the imagery script was read out loud to each participant. Participants were asked to imagine the putting movement as well as the ball rolling toward the target and stopping on the target, as predefined by the script. They were further told to imagine from an internal perspective, to incorporate all the senses in their imagery, and to try and imagine as clearly and as vividly as possible. The information on imagery perspective, imagery modality, and imagery vividness was intentionally given in order to control for as many aspects during imagery as possible and to optimize the efficacy of the imagery intervention (cf. Holmes & Collins, 2001). As soon as the reading was finished, participants imagined repeatedly the putting movement on their own. Participants were asked to hold their eyes closed during their imagery and to slightly raise their index finger each time they had finished a putt in their minds. This procedure allowed the participant to concentrate on themselves and their imagery and, at the same time, to make it possible for the experimenter to control for the number of imagined putts per block without disturbing the participants' imagery. Next, during actual putting, participants were instructed to putt as accurately as possible to the target, on which the ball was supposed to stop. No technical instructions were given. Finally, participants filled out a post-experimental questionnaire at the end of each practice session.

No practice (NP; control) group. During the acquisition phase, the control group neither imagined nor executed the putt.

4.2.3.3 Post- and retention-test

Participants were retested after the acquisition phase, as well as after a retention interval of three days. Prior to post-test and retention-test assessment, the same standard five-point calibration procedure was used to calibrate the eye-tracking system. Next, each participant performed again the two warm-up putts followed by 20 putts. Both their gaze behavior and putting performance were measured. Following this, all participants completed the splitting task in order to determine their final mental representation structures of the putting movement.

4.2.4 Data analysis

4.2.4.1 Performance

By capturing the final ball position after each putt, putting performance was assessed. From these data, two outcome variables were calculated for each test day. Specifically, based on the *x* and *y* coordinates of each putt with the center of the target as origin of the axes, two-dimensional error scores were determined (see Hancock et al., 1995). Accordingly, putting accuracy was measured by mean radial error (MRE). MRE is defined as a subject's average distance each putt came to the center of the target in mm. Putting consistency was measured by bivariate variable error (BVE), analogous to variable error in one-dimensional analyses. BVE was defined as the square root of a subject's k shots' mean squared distance from their centroids in mm. A subject's centroid is a positionally typical shot whose coordinates are given by the average *x* and average *y* value of a subject's shots in mm.

Initial putting performance of the three groups was compared by way of two separate one way ANOVAs on each of the two performance variables (i.e., accuracy and consistency) at pre-test. For putting performance over time, a 3 × 3 (*test day* [pre, post, retention] × *group* [PP, CP, NP]) ANOVA with repeated measures on the first factor was performed on each of the dependent variables. For post-hoc analysis, independent t-tests were conducted. Cohen's *d* was used as an estimate of effect size (Cohen, 1992).

4.2.4.2 Mental representation structure

Each participant's mental representation structure was determined by way of a cluster analysis. With the help of this procedure, the information on the distances and grouping of BACs as obtained by the splitting task was transformed into dendrograms. These cluster solutions (i.e., dendrograms) outlined the structure of the BACs of the putt. For the purpose of the present study, mean group dendrograms were calculated (for more details see Schack, 2012). An alpha-level of $\alpha = .05$ was chosen for all cluster analyses, resulting in a critical value $d_{crit} = 3.41$. To explain, BACs in a given cluster solution were considered not related when being linked above this critical value, while BACs were considered related when being linked below this value and thus resulted in a cluster. To compare cluster solutions, two analyses were conducted. First, analyses of invariance were used to learn about differences between cluster solutions (Lander 1991, 1992; see Schack, 2012). Accordingly, cluster solutions are considered different (i.e., variant) for $\lambda < .68$, while cluster solutions are considered the same (i.e., invariant) for $\lambda \geq .68$. Second, to further examine the similarity between cluster solutions and a reference, the adjusted rand index (ARI; Rand, 1971; Santos & Embrechts, 2009) was used. The ARI serves as an index of similarity, ranging on a scale from -1 to 1. Indices between "-1" and "1" mark the degree of similarity between two cluster solutions, with "1" indicating that two cluster solutions are the same. For the purpose of the present study, ARI was used to investigate the degree of similarity between mean group dendrograms and an expert dendrogram reflecting well the movement phases preparation, backswing, forward swing, impact, and attenuation (for more details, see chapter 4.2.2).

4.2.4.3 Gaze behavior

The quiet eye period was assessed by the duration of the final fixation before movement onset for each putt (for an overview, see Vickers, 2007, 2009). Accordingly, eye-tracking data were analyzed frame by frame. The number of frames for the final fixation prior to the initiation of the backswing was coded. From this, fixation duration for each putt was calculated. In line with previous studies (e.g., Vine & Wilson, 2010), the quiet eye analysis was performed on a subset of trials (i.e., every fourth); a total of 675 putts. Due to problems during the tracking of eye movements resulting in poor data quality, the data of one subject were excluded from subsequent data analyses.

In order to examine the quiet eye over time, a 3 × 3 (*test day* [pre, post, retention] × *group* [PP, CP, NP]) ANOVA with test day as within subjects factor and group as between subjects factor was performed on final fixation duration prior to movement onset. For post-hoc analyses, independent t-tests were conducted. Again, Cohen's *d* was used as an estimate of effect size (Cohen, 1992).

4.3 Results

4.3.1 Imagery ability

Participants scored 23.09 (*SD* = 3.15; 5.77 per item) on average for visual imagery ability, and 20.29 (*SD* = 4.96; 5.07 per item) on average for kinesthetic imager ability. Thus, participants' average score per item was approximately 6, *easy to see*, for the visual imagery ability scale, and 5, *somewhat easy to feel*, for the kinesthetic imagery ability scale. This is considered as being sufficient for subsequent mental practice (e.g., Smith & Collins, 2004; Smith et al., 2008). Moreover, separate one-way ANOVAs on overall scores, as well as on both scales separately, revealed no main effect of group (overall imagery ability: $F(2,42) = .866$, $p = .428$, $\eta_p^2 = .040$; visual imagery ability: $F(2,42) = .807$, $p = .453$, $\eta_p^2 = .037$; kinesthetic imagery ability: $F(2,42) = .404$, $p = .670$, $\eta_p^2 = .019$), indicating similar imagery ability for each of the three groups. Thus, novices in the three groups did not differ in their reported imagery ability.

4.3.2 Manipulation check

For the CP group, participants' manipulation check responses were analyzed to control whether participants adhered to the instructions given during mental practice sessions. With respect to imagery content, each participant mentioned in their imagery descriptions both the putting movement and the ball rolling. For the internal imagery perspective, mean scores during acquisition phase were 6.29 (*SD* = .69), *very often*, and for external imagery perspective 2.36 (*SD* = 1.42), *rarely*. Thus, participants of the CP group performed their imagery mainly from an internal perspective. In addition, participants found it easy to "see" and to "feel" the movement while imaging. Specifically, participants scored an average of 5.47 (*SD* = .96), *somewhat easy to see*, for visual imagery and 4.78 (*SD* = 1.33), *somewhat easy to feel*, for kinesthetic imagery. Moreover, participants in general found it *easy* to follow the instructions during imagery, as indicated by mean scores of 5.52 (*SD* = 1.04). Also, none of the participants reported any problems during imagery sessions. From this, it can be assumed that participants of the CP group had been able to perform the imagery as instructed. This was considered a prerequisite for subsequent data analyses.

4.3.3 Performance

Mean radial error (MRE) and bivariate variable error (BVE) of the three groups from pre-, to post- and to retention-test is displayed in Figures 4.1 and 4.2. Details on the descriptive statistics are listed in Table 4.3.

Table 4.3

Descriptive statistics for performance outcome variables in cm across pre-test, post-test, and retention-test for the no practice (n = 14), the physical practice (n = 15) and the combined practice (n = 16) groups

	Pre-test		**Post-test**		**Retention-test**	
	MRE *M (SD)*	***BVE*** *M (SD)*	***MRE*** *M (SD)*	***BVE*** *M (SD)*	***MRE*** *M (SD)*	***BVE*** *M (SD)*
NP	70.75 (18.10)	80.68 (17.43)	54.18 (13.73)	61.58 (15.26)	60.07 (21.03)	69.88 (24.07)
PP	71.31 (24.53)	84.23 (27.10)	44.02 (11.48)	53.71 (16.26)	41.64 (14.75)	50.31 (17.18)
CP	71.76 (22.96)	82.06 (23.99)	41.01 (11.20)	47.04 (10.62)	37.50 (7.43)	46.43 (12.09)

Note: NP = no practice; PP = physical practice; CP = combined mental and physical practice; MRE = mean radial error (accuracy); BVE = bivariate variable error (consistency).

For accuracy, a repeated measures ANOVA on MRE indicated a significant *test day* × *group* interaction, $F(4,84) = 4.042$, $p = .005$, $\eta_p^2 = .161$. Post-hoc analyses revealed that both the CP group, $t(28) = -2.893$, $p = .007$, $d = 1.05$, and the PP group, $t(27) = -2.167$, $p = .039$, $d = .80$, putted significantly more accurate than the NP group after acquisition phase. No significant differences were found between the PP and the CP group, $t(29) = -.740$, $p = .465$, $d = .27$. Similarly, after a retention-interval of three days, both the CP group, $t(15.830) = -3.813$, $p = .002$, $d = 1.43$, and the PP group, $t(27) = -2.748$, $p = .011$, $d = 1.01$, performed with greater putting accuracy compared to the NP group, while no difference was found between the PP and the CP group, $t(29) = -.998$, $p = .327$, $d = .35$.

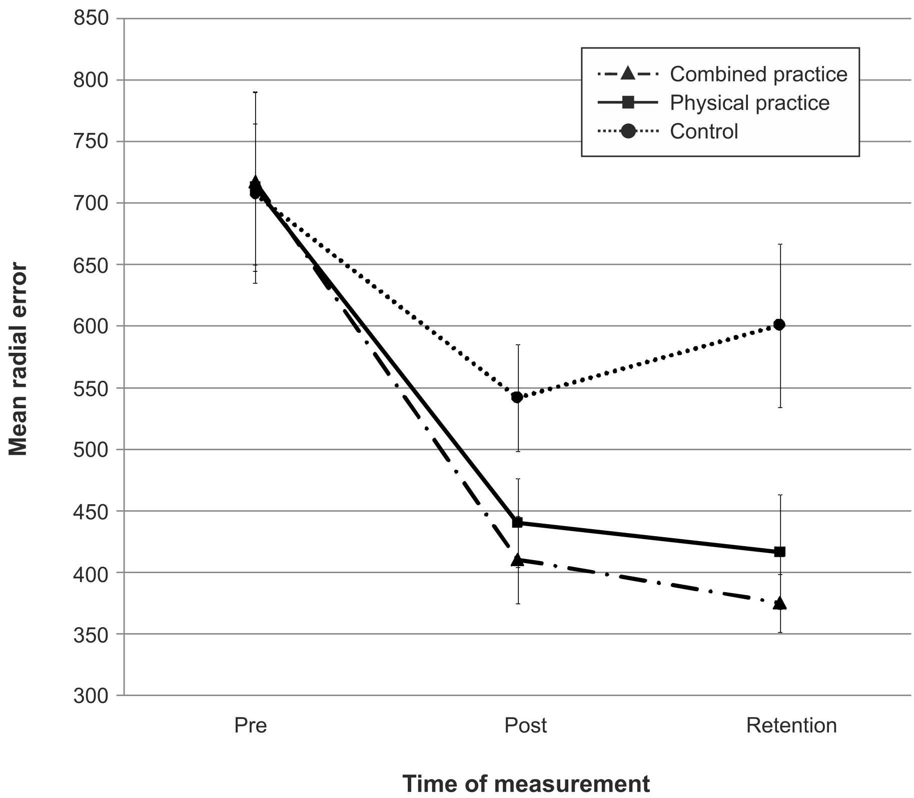


Figure 4.1. Mean radial error (i.e., accuracy) in mm from pre-test to post- and retention-test. The different lines relate to the different conditions (i.e., no practice, physical practice or combined mental and physical practice). Error bars represent standard errors.

For consistency, a repeated measures ANOVA on BVE indicated a significant *test day* × *group* interaction, $F(4,84) = 3.615$, $p = .009$, $\eta_p^2 = .147$. Post-hoc analyses revealed that the CP group putted more consistently compared to the NP group after acquisition phase, $t(22.815) = -2.989$, $p = .007$, $d = 1.11$, while this was not the case for the PP group, $t(27) = -1.343$, $p = .191$, $d = .50$. Furthermore, the CP and the PP group did not differ in their putting consistency, $t(29) = -1.361$, $p = .184$, $d = .49$. For retention-test, both the CP group, $t(18.590) = -3.299$, $p = .004$, $d = 1.23$, and the PP group, $t(27) = -2.534$, $p = .017$, $d = .94$, performed with greater consistency in comparison to the NP group, whereas the PP and the CP group did not differ, $t(29) = -.732$, $p = .470$, $d = .26$.

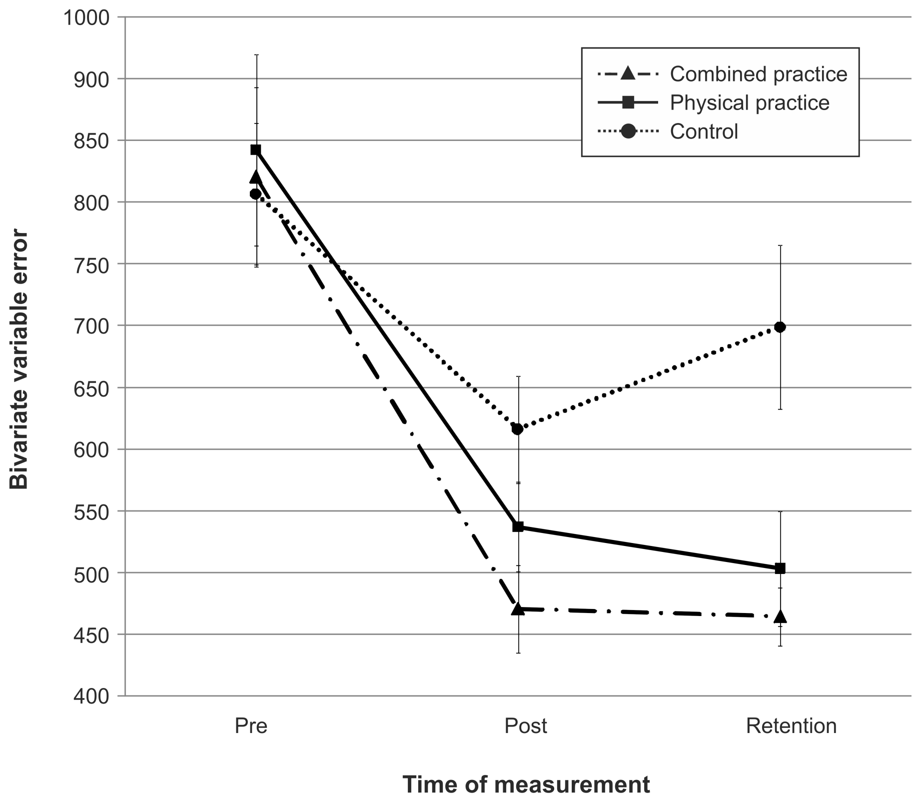


Figure 4.2. Bivariate variable error (i.e., consistency) in mm from pre-test to post- and retention-test. The different lines relate to the different conditions (i.e., no practice, physical practice or combined mental and physical practice). Error bars represent standard errors.

In sum, while the combination of mental and physical practice as well as physical practice only led to better putting accuracy in the present study, it was only the combined practice that led to more consistent putting after the acquisition phase. After a three day retention interval, however, both types of practice prove superior in improving putting accuracy and consistency compared to no practice (see also Figures 4.1 and 4.2).

4.3.4 Mental representation structure

Mean group dendrograms of the three groups from pre-, to post- and to retention-test are displayed in Figures 4.3 to 4.5.

Combined mental and physical practice (CP) group. As seen in Figure 4.3, no structure was evident for the CP group prior to the acquisition phase. In detail, the mean group dendrogram of the CP group revealed only one cluster pertaining to the preparation phase (BAC 2 and 3). After the acquisition phase, however, the mean group dendrogram was comprised of four clusters relating to different phases of the movement (i.e., preparation phase (BAC 2, 3), forward swing (BAC 8, 9), impact (BAC 10, 11, 13), and attenuation (BAC 14, 16)). Cluster solutions of the CP group for post- and retention-test were similar, with the only difference being that after the three day retention interval, the cluster pertaining to preparation phase involved one more concept (BAC 2, 3, 4). Thus, for the CP group, the number of functional clusters increased over the course of acquisition phase, with the representation structure becoming more elaborate over time. The descriptive changes over time observed in the dendrograms were confirmed by analyses of invariance. Specifically, while the cluster solutions for pre- and post-test ($\lambda = .24$) as well as for pre- and retention-test ($\lambda = .24$) were variant (i.e., significant changes in the structures over practice), the two cluster solutions of post- and retention-test ($\lambda = .71$) were invariant (i.e., no meaningful differences between representation structures). Furthermore, increases in adjusted rand indices from pre-test ($ARI_{pre} = .12$) to post-test ($ARI_{post} = .35$) and to retention-test ($ARI_{retention} = .50$) indicate increasing similarity in comparison to the expert structure and as such emphasize that the changes in representation structure reflect a functional development.

Physical practice (PP) group. In contrast to the CP practice group, the mean group dendrograms of the PP group revealed minimal clustering over time (see Figure 4.4). Specifically, no clustering was evident for the PP group prior and after the acquisition phase. However, the retention test revealed one cluster pertaining to preparation phase (BAC 2 and 3). As there was no overlap in the clustering of the

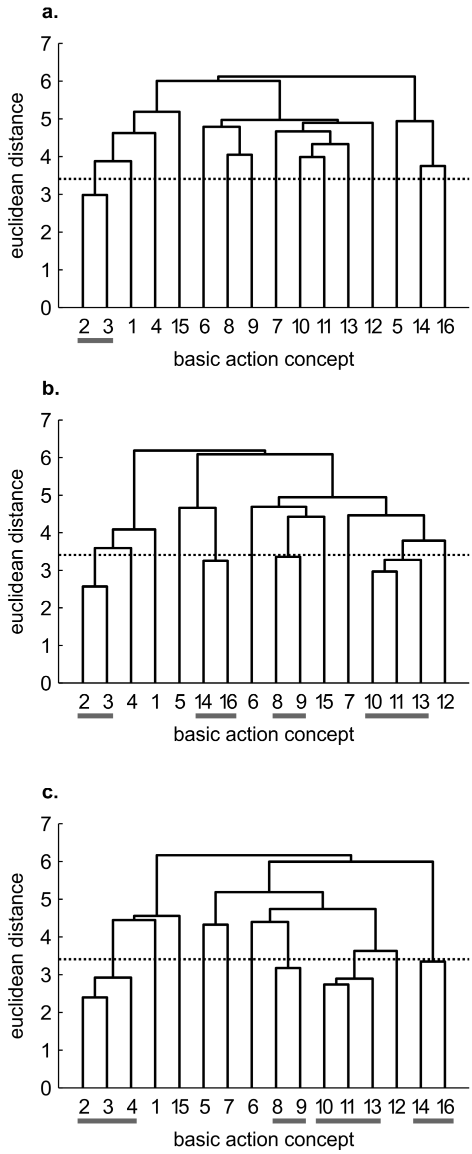


Figure 4.3. Mean group dendrograms of the combined mental and physical practice group (n = 16) for the golf putt at (a) pre-test, (b) post-test and (c) retention-test. The numbers on the x-axis relate to the BAC number, the numbers on the y-axis display Euclidean distances. The lower the link between related BACs, the lower is the Euclidean distance. The horizontal dotted line marks d_{crit} for a given α-level ($d_{crit} = 3.41; \alpha = .05$): links between BACs above this line are considered not related; horizontal grey lines on the bottom mark clusters. BACs: (1) shoulders parallel to target line, (2) align club face square to target line, (3) grip check, (4) look to the hole, (5) rotate shoulders away from the ball, (6) keep arms-shoulder triangle, (7) smooth transition, (8) rotate shoulders towards the ball, (9) accelerate club, (10) impact with the ball, (11) club face square to target line at impact, (12) follow-through, (13) rotate shoulders through the ball, (14) decelerate club, (15) direct clubhead to planned position, and (16) look to the outcome.

different cluster solutions, analysis of invariance resulted in values of 0. Interestingly, although not obvious at first glance, increasing adjusted rand indices over time (ARI_{pre} = 0, ARI_{post} = 0, $ARI_{retention}$ = .12) suggest a minimal development in direction of the expert representation structure.

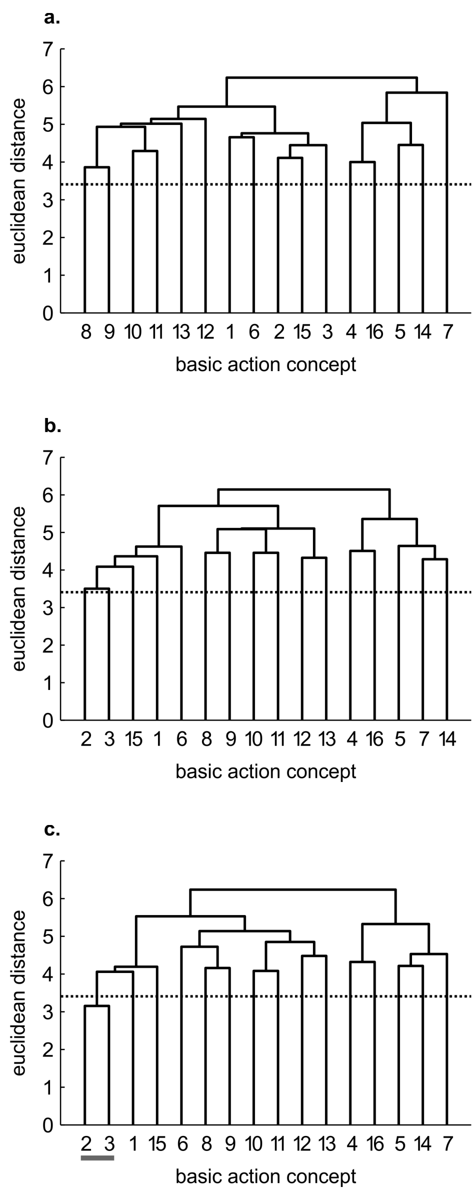


Figure 4.4. Mean group dendrograms of the physical practice group (n = 15) for the golf putt at (a) pre-test, (b) post-test and (c) retention-test (α = .05; d_{crit} = 3.41).

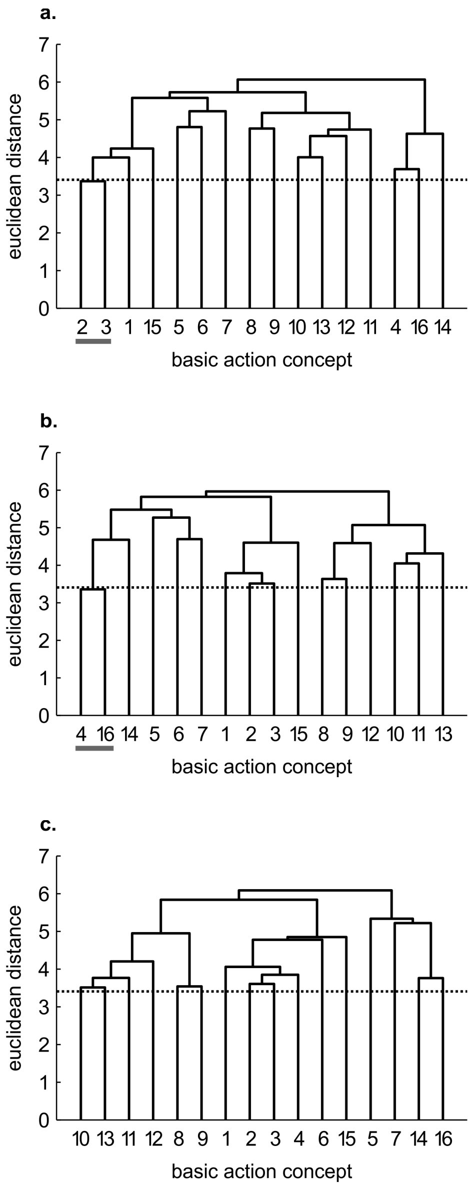


Figure 4.5. Mean group dendrograms of the control group (n = 14) for the golf putt at (a) pre-test, (b) post-test and (c) retention-test (α = .05; d_{crit} = 3.41).

No practice (NP) group. Prior to the acquisition phase, the mean group dendrogram of the NP group revealed one cluster relating to the preparation of the putting movement (BAC 2 and 3; see Figure 4.5). After the acquisition phase, however, a new structure emerged which reflected one cluster comprised of two functionally unrelated concepts (BAC 4 and 16). Specifically, although being related in the sense that both concepts involve the word "look", these concepts are not related during movement execution. Thus, this relation is based on superficial rather than on functional characteristics. After the three day retention interval, no clusters were evident in the mean group dendrogram of the NP group. Again, analysis of invariance resulted in values of 0, as there was no overlap in the clustering of the different cluster solutions. When being compared to the expert structure, ARIs revealed a slight decrease in the degree of similarity from pre-test ($ARI_{pre} = .12$) to post-test ($ARI_{post} = -.02$) to retention-test ($ARI_{retention} = .00$).

In sum, prior to the acquisition phase, mental representations revealed little to no structures. Over the course of practice, however, combined practice led to a significant development in mental representation structure, while physical practice only as well as no practice led to only minor or no changes in mental representation structure (see also Figures 4.3-4.5).

4.3.5 Gaze behavior

Mean durations of the final fixations prior to putting for the three groups across pre-, post- and retention-test are presented in Figure 4.6. A repeated measures ANOVA on final fixation duration indicated a significant *test day* × *group* interaction, $F(4,82) = 6.532$, $p < .001$, $\eta_p^2 = .242$. Post-hoc analyses revealed that the CP group demonstrated longer fixation durations compared to the NP group, $t(20.928) = 2.079$, $p = .050$, $d = .74$ after three days of practice. In contrast, no significant difference between the PP group and the NP group was evident, $t(26) = 1.167$, $p = .254$, $d = .44$. Furthermore, the CP group and the PP group did not differ in their fixation duration after acquisition phase, $t(28) = .954$, $p = .348$, $d = .35$. After three days of rest, the CP group once more demonstrated significantly longer fixation durations compared to the NP group, $t(17.563) = 2.887$, $p = .010$, $d = 1.03$. Again, fixation durations of the PP group were not different from those of the NP group, $t(26) = 1.418$, $p = .168$, $d = .54$. The difference in fixation duration between the CP group and the PP group failed to reach significance, $t(28) = 1.753$, $p = .090$, $d = .65$.

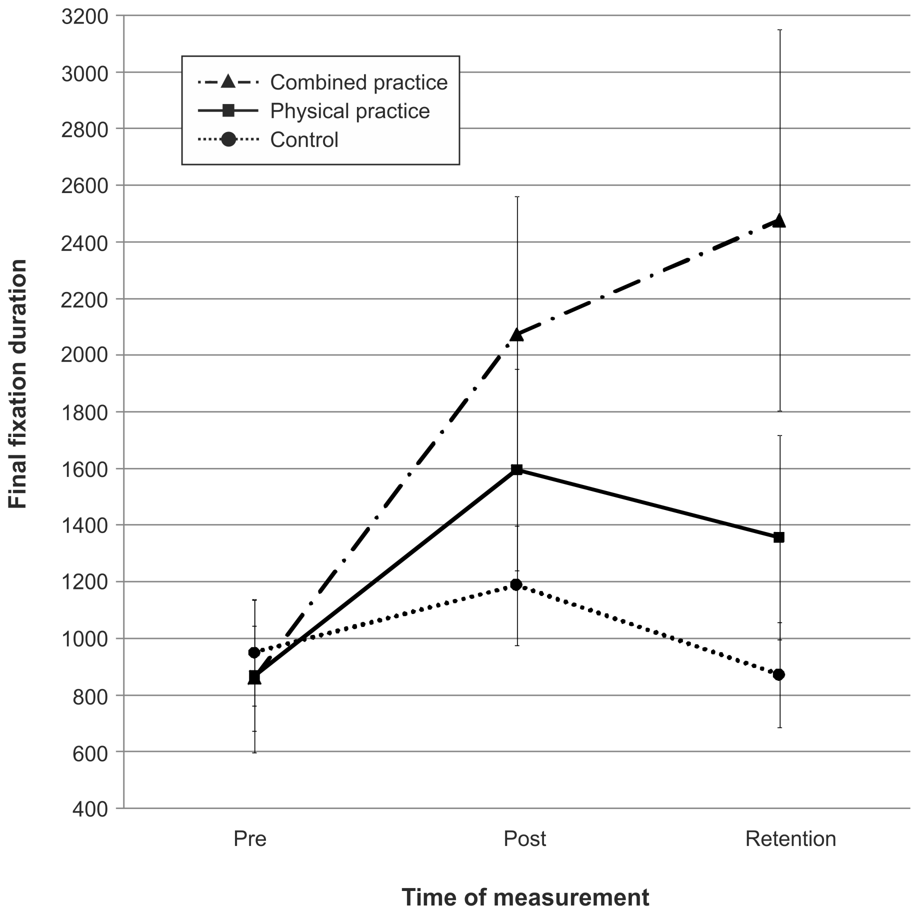


Figure 4.6. Mean quiet eye duration in ms from pre-test to post- and retention-test. The different lines relate to the different conditions (i.e., no practice, physical practice or combined mental and physical practice). Error bars represent standard errors.

In sum, only the combined practice led to longer final fixation durations compared to no practice after acquisition phase. Similarly, after three days of rest, the duration of the final fixation remained longer for the combined practice compared to no practice, while this was not the case for physical practice. Interestingly, after the retention interval, a tendency was becoming evident that the combined practice had led to even longer fixation durations than the physical practice. Thus, combined mental and physical practice as opposed to physical practice only led to a longer quiet eye period during the acquisition of putting skill in comparison to no practice (see also Figure 4.6).

4.4 Discussion

The purpose of the present study was to examine the influence of physical practice and combined mental and physical practice on the mental representation of a golf putt, gaze behavior prior to putting, and putting performance. By doing so, we aimed at gaining further insights into the perceptual-cognitive background of performance changes during motor skill acquisition, both as a result of mental and physical practice.

Overall, putting performance improved over time, with both types of practice leading to improved accuracy and consistency. Importantly, improvements in performance persisted over three days of no practice, reflecting permanence. In this sense, and according to the traditional view of motor learning, both practice types led to persisting performance improvements, and thus motor learning (e.g., Magill, 2011; Schmidt & Lee, 2011). Relatively permanent changes in putting performance as a result of practice as found in the present study are in line with the general idea that repeatedly executing a motor action leads to improved performance of that motor action (e.g., Newell & Rosenbloom, 1981). Interestingly, the combined mental and physical practice did not lead to superior putting performance in comparison to the practice that did not involve the additional mental practice. This is surprising as a combination of both types of practice has been suggested to outperform practice that does not involve mental practice (e.g., Hall et al., 1992).

One reason why additional mental practice might not have contributed to superior overt putting performance in the present study is the smaller relative magnitude of effect that mental practice has in comparison to physical practice. Meta-analyses investigating the relative magnitude of effect between mental and physical practice emphasize the superiority of physical practice over mental practice (e.g., Driskell et al., 1994; Feltz et al., 1988). For instance, Driskell et al. (1994) reported strong effect sizes for physical practice (d = .78) and moderate effect sizes for mental practice (d = .53). Hence, the smaller magnitude of effect may be one reason why additional mental practice in the present study did not prove effective in further enhancing motor performance and supporting motor learning on the motor output level. As a consequence, extending the practice phase (i.e., amount of sessions and/ or amount of trials) may elicit a distinct effect of additional mental practice.

Related to that, a second plausible explanation for the lack of differences between combined practice and physical practice only may be that mental practice effects may not primarily become evident on the performance level during early skill acquisition. It is conceivable that, at an early stage of motor learning, mental practice affects the perceptual-cognitive level, but these changes do not necessarily have to transfer one-to-one to the motor output level, and thus may not or only minimally be reflected in overt outcome performance. This is in line with the general suggestion that novices may not benefit from mental practice as much as experts do in terms of overt performance (e.g., Driskell et al., 1994), and thus mental practice more likely proves beneficial for improving overt performance at a more advanced level of skill. As an extension, we suggest that, although mental practice is not as effective as physical practice in improving overt performance in novices, it does have an influence on the motor system, and on the perceptual-cognitive background of motor action in particular (for more details, see discussion below).

With respect to the representation of the golf putt in long-term memory, mental representation structures developed over the course of practice, with the combined practice leading to the most elaborate representation structures relative to an expert structure. In contrast, physical practice led to only minimal changes in direction of an expert structure. No such changes in representation structures were observed in the control condition. The results of the present study are in line with previous research on differences in mental representation of complex action according to skill level, with well-experienced athletes revealing more structured representations than their less-experienced counterparts (e.g., Bläsing et al., 2009; Schack & Mechsner, 2006; Velentzas et al., & Schack, 2010). Moreover, the present findings further support the development of representation structures over the course of learning (e.g., Frank et al., 2013; Frank et al., 2014; Land et al., 2014). As expected, representation structures developed most during combined mental and physical practice, while during physical practice, only minimal changes were evident. Hence, the present study replicates the findings from Frank et al. (2014). Similarly to Frank et al. (2014), representation structures of the group that incorporated mental practice into their practice regime revealed several functional clusters of BACs, pertaining to the different movement phases of the putt (i.e., preparation, forward swing/ impact, attenuation), both after practice and after a retention interval of three days. Instead, this was not the case for participants not incorporating mental practice into their practice regime. Thus, the results of the present study confirm the findings by Frank et al. (2014) such that when spending time practicing mentally during skill acquisition, the mental representation structure of a complex movement develops functionally (i.e., becomes more similar to the representation of an expert). In this sense, the present study further supports the idea that mental practice adds to the cognitive adaptation process during motor learning.

A main aim of the present study was to further investigate the perceptual-cognitive background of performance changes by examining perceptual changes during motor skill acquisition. With respect to gaze behavior, the combined mental and physical practice led to longer quiet eye periods (i.e., longer fixation durations prior to putting) compared to no practice. No differences were evident between the CP group and the PP group after the acquisition phase in the present study. However, while not statistically significant, the difference between the CP group and the PP group after the retention interval indicated a medium effect size ($d = .65$), with the combined practice leading to longest fixation durations. Overall, our findings fit well into the body of research on the quiet eye reporting longer quiet eye durations for higher-skilled athletes in comparison to lower-skilled athletes (e.g., Vickers, 1992; Vickers, 1996; for an overview, see Vickers, 2007). Moreover, our results extend findings on differences in quiet eye behavior by providing insight into the change in quiet eye behavior over the course of practice. To our knowledge, the present study is the first to show that quiet eye duration changes in novices practicing a complex movement. In the present study, the quiet eye period of the CP group became more similar to that of an expert. More specifically, while quiet eye durations of expert golfers have been reported to last between two and three seconds on average (e.g., Vickers, 2007), the CP group revealed a mean duration of 2.1 s after the acquisition phase and 2.5 s after the retention interval. This last fixation period prior to movement onset is thought to serve to pick up environmental cues and to program the planned movement in an appropriate manner in order to prepare subsequent movement execution (Vickers, 2009). Accordingly, the present findings suggest that combined mental and physical practice contributes to a longer information-processing period during which the movement is pre-programmed. Furthermore, the fact that combined practice indicated a medium effect to produce longer quiet eye periods compared to physical practice after the retention-interval suggests that the mental component of the combined practice (i.e., repeatedly imagining the movement without overt movement execution) may contribute to longer information-processing prior to movement onset. However, future research has yet to test this proposition. In addition, a further valuable objective for future research would be to investigate the relationship between mental representation and quiet eye period. Taking into consideration the fact that both more elaborate representations in long-term memory and longer fixation durations were observed as a result of combined mental and physical practice in the present study, it is likely that more elaborate representations led to more elaborate information-processing during movement preparation. Therefore, future studies should look more closely at the causality of this relationship.

Taken together, the combined mental and physical practice led to both perceptual-cognitive changes and changes in motor performance in the present study. That is, combined practice contributed to both better order formation in memory (i.e., more elaborate representation structures of the putt) and longer information processing prior to movement execution (i.e., longer quiet eye durations before initiation of the putting movement) as well as to improved putting performance (i.e., accuracy and consistency). In contrast, physical practice led to improved putting performance, but neither to any substantial changes in representation structures nor to longer quiet eye durations. From this, one may even speculate that it is the mental component of the practice that promotes the perceptual-cognitive adaptation process during motor learning.

The findings of the present study point to the differential effects of mental and physical practice on the perceptual-cognitive level and the motor output level during early skill acquisition. From this, it seems that the adaptation of these levels within the motor system is to some degree independent, and that mental practice during early skill acquisition influences more the 'mental side' (i.e., perceptual-cognitive level) and physical practice influences more the 'sensorimotor side' (i.e., the motor output level) of a motor action. However, if the objective is the acquisition of a motor skill and thus motor learning, why should the perceptual-cognitive adaptation within the motor system matter? Although both levels of the motor system seem to develop independent of each other to some degree, they are thought to interrelate. Although changes on the perceptual-cognitive level did not (yet) find expression on the motor output level after three days of practice in the present study, they may do so after a longer period of practice. Moreover, further improvements in performance are likely tied to the extent of previous perceptual-cognitive adaptation. It is likely that the rate of performance improvements will be much faster given a solid perceptual-cognitive basis (or top, respectively) compared to the rate of performance improvements without such a basis. One might even speculate that the perceptual-cognitive adaptation will prove important when it comes to transfer of what has been learnt to another task. Similarly, long-term retention may prove better, and thus, loss of motor skill may be reduced when having practiced mentally and having promoted the perceptual-cognitive background accordingly. Future studies will be necessary to test these hypotheses.

From a more general point of view, the motor system can be viewed as being an entity composed of different levels interacting during the execution of a motor action. In other words, action organization can be considered to take place on different levels within the hierarchically organized motor system (e.g., CAA-A; Schack, 2004). In that sense, each level of the system may (or may not) change to a different degree during motor learning. To put it differently, motor learning may best be considered a multilevel process. An advantage of such a hierarchical view is that a system and its components are being looked at both independently and together at the same time. From this point of view, it seems promising to further investigate the interdependence of the levels working together in the production of a motor action, and to learn more about the integration (or separation) of single levels within the motor system, both at earlier as well as at later stages of learning.

Accordingly, motor action can be viewed as a result of perceptual, cognitive and motor components. As each of the components is part of the motor system, each is likely to change over the course of motor learning. As such, motor learning may involve learning processes both on the perceptual-cognitive and on the motor output level. With the present study, we sought to look closer at these changes during motor learning, and to draw conclusions for each of the components and the motor system as a whole. Our findings suggest that the motor system as a whole is influenced by both mental and physical practice. However, each type of practice likely influences the individual components, the perceptual-cognitive and the motor output components, to a different degree. That is, combined mental and physical practice seems to influence the motor system differently than physical practice only, with combined practice influencing the motor system more so on a perceptual-cognitive level.

From this point of view, examining outcome performance may not provide sufficient insight to the adaptation processes associated with motor learning. A closer look into the motor system, thereby by considering perceptual-cognitive and motor output processes at the same time, might help to gain further insights into learning processes. If future studies approached motor learning from such a multilevel perspective, this may shed further light on open questions regarding the motor system. Such an approach may even help to solve existing contradictions, that originated by seemingly ambiguous results derived from studies that exclusively consider the motor output level of the motor system. For instance, mental practice has been found to influence performance of a motor action (1) not at all, (2) less than physical practice, (3) more than physical practice (for an overview, see Wohldmann, Healy, & Bourne, 2007). Based on these results, ambiguous conclusions have been drawn regarding whether or not mental practice promotes the learning of a motor action. This illustrates well that, in some cases, approaching motor learning from a one-dimensional view does not provide a satisfactory solution for seemingly ambiguous findings. Consequently, a closer look onto the motor system is necessary to resolve contradictions as the one described above. Approaching motor learning from a multilevel perspective, thereby considering both perceptual-cognitive changes as well as changes in motor performance may help to gain a more thorough picture of the processes taking place during motor skill acquisition. To this extent, future research in the field should consider motor learning both from the perceptual-cognitive and the motor point of view.

To conclude, the present findings demonstrate that a combination of mental and physical practice brings about both perceptual-cognitive adaptations (i.e., functional adaptations in the representation structure of a complex action in memory and in the information processing prior to movement onset) and adaptations in motor performance. According to the results of the present study, repeatedly imagining and executing a movement prompts changes on both a perceptual-cognitive level and a motor output level within the motor system. Hence, with this study we were able to give comprehensive insights into the perceptual-cognitive background of performance changes during motor learning. Furthermore, by employing a multilevel approach to motor learning, we demonstrated the value of looking at motor skill acquisition from different angles. Future studies in the area of motor learning in general as well as the area of mental practice in particular might benefit from approaching the phenomena of interest in this way. In doing so, and by using a combination of methods, such a multifaceted view may contribute to bring forward research on some of the remaining unanswered questions in our field.

5 GENERAL DISCUSSION

5.1 Key findings

The first study of the present work aimed at shedding light on the development of one's mental representation of a complex action during motor learning. Therefore, the question was examined whether the mental representation structure of a complex action changes over the course of practice, and if so whether this change reflects a development toward a more elaborate and functional structure, such as that of an expert. Together with improvements in putting performance, mental representations of the putt were found to change with practice, developing toward more functional ones. Specifically, mental representation structures of the (physical) practice group changed from pre-, to post- and to retention-test, and became more similar to a golf expert structure over the course of practice, reflecting distinct phases of the putting movement (i.e., preparation, forward swing, and impact). Instead, mental representation structures of the (no practice) control group, neither executing nor practicing the putt, did not change and remained dissimilar in comparison to an expert structure (for details on the results, see chapter 2). This study shows that, along with improvements in (overt) performance, the (covert) mental representation of a complex action develops as a result of practice.

The goal of the second study was to provide further insights into the development of one's mental representation of a complex action according to type of practice, with a particular emphasis on mental practice. Hence, the question was investigated whether the mental representation structure of a complex action changes as a result of both mental and physical practice as well as a combination of both, and if so whether the changes reflect a development toward a more elaborate and functional structure. In line with findings from study one, mental representations of the putt developed over the course of practice. Interestingly, mental practice, either solely or in combination with physical practice, led to even more elaborate representations compared to physical practice only. Specifically, mental representation structures of the groups practicing mentally became more similar to a functional structure, thereby reflecting well the functional phases of the putting movement, whereas those of the physical practice group revealed less development toward a functional structure. Furthermore, putting performance improved over the course of practice, reflecting the well-known pattern of magnitude of improvement according to type of practice. Specifically, combined mental and physical practice was most effective, followed by physical practice, mental practice and no practice (i.e., combined practice > physical practice > mental practice > no practice). Statistically, the combined practice group proved more effective than mental practice only and no practice with respect to performance (for details on the results, see chapter 3). Hence, findings from the first study were replicated such that, along with improvements in performance, mental representation of a complex action developed as a result of practice. More importantly, however, the second study shows that mental practice adds to representation development leading to even more elaborate representations. Notably, these (covert) adaptations did not seem to transfer one-to-one to the (overt) motor output.

The aim of the third study was to further examine the perceptual-cognitive background of performance changes that occur within the motor action system as a result of mental and physical practice, thereby providing insights into both mental representations and gaze behavior during complex action. Accordingly, the question was investigated whether mental representation structure of the putt and gaze behavior during putting change with both physical and combined mental and physical practice, and if so whether the changes reflect a functional development. Similar to findings of study two, combined mental and physical practice led to more developed representation structures of the putt compared to physical practice alone. As an extension, combined practice as well led to more elaborate gaze behavior prior to execution of the putt. Specifically, final fixations prior to the onset of the putting movement were longer after practice for the group practicing mentally in addition to physical practice in comparison to the control group. This was not the case for the group practicing physically only. Putting performance improved similarly in both practice groups over the course of practice (for details on the results, see chapter 4). Thus, the results of study three once more indicate that it is the mental component of the practice that led to more developed representation structures. Importantly, along with mental representation development, gaze behavior seems to develop as well. However, similar to study two, these (covert) perceptual-cognitive adaptations were not evident on (overt) motor output.

5.2 Implications

5.2.1 The adapting motor action system

5.2.1.1 Behavioral changes

Regarding changes in motor performance, findings of the present work are in line with traditional and contemporary research on motor learning, reporting performance improvements as a result of both mental and physical practice. First, the findings of the present work match with the general finding that performance improves with practice. In each of the three studies conducted, performance improved over the course of practice (for details, see chapter 2.3, 3.3, and 4.3). Second, the findings of the present work are in line with the general pattern found for different practice types such that mental practice can improve performance, but in general not to the same extent than physical practice. Moreover, a combination of mental and physical practice has been found to be as effective as or even superior to physical practice. This pattern was reflected in the results of study 2 and 3, and as such further supports that performance improvements during motor learning are dependent on practice type (for details, see chapters 3.3 and 4.3). Thus, the changes in performance across the three learning studies reflect well the state of the art in motor learning research in general and mental practice research in particular. In accordance with previous research, our findings further support that changes on a motor output level as a result of both mental and physical practice take place within the motor action system and differ according to practice type (for detailed discussions, see chapters 2.4, 3.4, and 4.4).

5.2.1.2 Perceptual-cognitive changes

A main objective of the present work was to give comprehensive insights into the perceptual-cognitive adaptations within the motor action system, as a result of both mental and physical practice. Thus, in addition to behavioral adaptations as reflected by motor performance, the perceptual-cognitive adaptations in terms of functional changes in mental representation and gaze behavior were of particular interest to the present work.

Across the three studies, along with performance improvements, the structure of mental representations developed toward a more elaborate structure, reflecting action-related order formation in long-term memory. As has been described before, this finding fits well into and extends the body of research on the characteristic differences in mental representation structure between unskilled and skilled athletes. While novices' representations have been found to be unstructured, experts rely on structured representations in the sense that they match well with the biomechanical and functional demands of the task. In the present work, representations of novices turned from unstructured into more structured ones over the course of practice, with the structures becoming more similar to an expert structure (for details, see chapters 2.3, 3.3, and 4.3). Thus, along with changes in performance, a *cognitive adaptation* in terms of order formation in long-term memory within the human action system was evident (for detailed discussions, see chapters 2.4, 3.4, and 4.4).

Furthermore, mental representation structure was found to develop differently during skill acquisition depending on practice type. It became evident that the influence of mental and physical practice differs in terms of the development of mental representation structure. Specifically, findings from study 2 and 3 revealed that mental representation structure became most elaborate with mental practice. When mental practice was part of the practice regime, mental representation structure developed even more toward an expert structure compared to the physical practice only condition (for details, see chapters 3.3 and 4.3), reflecting a higher degree of action-related order formation in long-term memory. Thus, findings on the cognitive adaptation within the motor action system as reported from study 1 could be further extended such that mental practice has been found to add to the functional development in mental representation structure. From this, it seems that mental practice adds to the cognitive adaptation within the motor action system (for detailed discussions, see chapters 3.4 and 4.4).

Finally, findings from study 3 helped to shed further light on the perceptual-cognitive background of performance changes as induced by physical and mental practice. It was shown that a combination of mental and physical practice led to both more elaborate mental representation structures and more functional gaze behavior prior to movement execution in comparison to physical practice alone (for details, see chapter 4.3), indicating that combined practice contributed to both a cognitive and a perceptual adaption during the learning of a motor action. This finding supports findings from study 1 and 2 and further extends them such that combined practice led not only to a cognitive, but to a *perceptual-cognitive adaptation* within the motor action system. In addition, this finding indicates that the perceptual-cognitive adaptation may be promoted by mental practice in particular (for a detailed discussion, see chapter 4.4).

In sum, according to the results of the present work, perceptual-cognitive changes as a result of mental and physical practice take place within the motor action system. As has been discussed, changes in mental representation structure and gaze behavior as found in the present work both fit well into the body of existing research and extend it. From this, the motor action system functionally adapts from a perceptual-cognitive point of view during motor learning in general and mental practice in particular.

5.2.2 Mental representation and its development with mental and physical practice

By approaching the motor action system from an architecture point of view, it was possible to gain further insights into the adaptation processes therein, thereby extending the traditional view (see chapter 1.3.1) by a perceptual-cognitive view on the learning of a motor action (see chapter 1.5.1). The present work on the influence of mental and physical practice elicited both behavioral adaptations (in terms of motor performance) as well as perceptual-cognitive adaptations (in terms of mental representation structures and gaze behavior) that occur over the course of learning within the motor action system (see chapter 5.2.1). While behavioral adaptations, as found in the three learning studies, fit well into the body of research on motor learning in general and mental practice in particular, the findings on perceptual-cognitive adaptations extend it. Specifically, the present work was the first to systematically examine the perceptual-cognitive adaptations within the motor action system as a result of mental and physical practice.

As previously described in more detail within the scope of the cognitive action architecture approach (CAA-A; see chapter 1.4), the learning of a motor action is considered as the adaptation of representational networks of complex action in long-term memory, and as such as stratification within the motor action system, resulting from changes of feature dimensions and related relative structures (see chapters 1.4.3 and 1.5.1). In line with the prediction derived from the CAA-A that motor learning would be reflected on the level of mental representation, mental representation structures were found to develop toward more elaborate structures with practice across the three studies. Along with performance improvements, mental representation structures developed with both physical practice (cf. study 1-3) and mental practice (cf. study 2-3).

Furthermore, according to the perceptual-cognitive hypothesis, mental practice is suggested to take place particularly on the representational levels of action organization, linking sensorimotor to mental representations and in this way leading to stratification within the motor action system (see chapters 1.4.4 and 1.5.1). In line with the predictions derived from the CAA-A that mental practice would lead to a functional development on the representational levels of action organization, mental representation structures were found to develop toward more elaborate structures with mental practice in the present work (cf. study 2-3). Importantly, in comparison to physical practice, mental practice was found to add to the functional development in representation structure over the course of learning, leading to more elaborate structures than physical practice (cf. study 2-3). Similarly, mental practice seems to add to the functional development in gaze behavior, leading to longer quiet eye durations (cf. study 3).

Interestingly, this perceptual-cognitive adaptation was not congruent with the behavioral adaptation such that the more elaborate representation structures and the more elaborate gaze behavior would be reflected one-to-one in terms of better performance. Despite the fact that mental practice was associated with more elaborate representations and more functional gaze behavior, this did not result in better performance in comparison to physical practice. From this, it seems that mental practice primarily induces (covert) perceptual-cognitive adaptations within the motor action system, stabilizing the representational networks of complex action, but does not necessarily translate into (overt) behavioral adaptations, resulting in observable differences in motor performance. Mental practice during early stages of learning seems to particularly influence the motor action system from within, leading to an inner refinement of action representation, thereby not necessarily transferring directly to the motor output levels (for more details, see also chapters 3.4 and 4.4 as well as below).

The findings of the present work extend contemporary research on mental representation of complex action conducted in the realm of the CAA-A. While, so far, research has mainly compared mental representation structure across skill levels (see chapters 1.3.2-1.3.4), the particular focus of the present work was directed toward changes in mental representation structure over time. The work at hand was the first to investigate mental representation structure of complex action in early skill acquisition experimentally and from a longitudinal point of view, thereby giving insights into the adaptations on the level of mental representation within the motor action system as a result of practice. Specifically, the present work systematically investigated mental representation and its development with mental and physical practice during early stages of learning. From this, motor learning can be considered as the adaptation on the level of mental representation such that the relations and the groupings of action concepts (i.e., mental representation structure) are modified over the course of learning and change toward more functional ones. As such, motor learning as induced by mental and physical practice reflects action-related order formation in long-term memory.

Importantly, by taking a perceptual-cognitive view on the motor action system, it was possible to gain further insights into the similarities and differences of mental and physical practice in promoting learning within the motor action system. This will be elaborated on in more detail in the following.

From the findings of the present work, both types of practice seem to lead to perceptual-cognitive as well as behavioral adaptations within the motor action system. Independent of practice type, motor learning seems to be reflected by changes in motor performance and changes in representation structure as well as in gaze behavior. Accordingly, with reference to the CAA-A, both the mental system and the sensorimotor system seem to change during motor learning as induced by mental and physical practice. However, and most notably, mental and physical practice seem to influence the levels of action organization within the motor action system to a different degree. Both types of practice were found to differentially influence the development of mental representation structure and as such seem to have their distinct contribution to the motor learning process within the adapting motor action system. Mental practice was associated with most developed representation structures, whereas physical practice was associated with best motor performance. This indicated that the learning of a motor action by physical practice differs from the learning of a motor action by mental practice with regard to the different levels of action organization.

Drawing on elaborations by Schack (2002, 2003, 2004, 2006, 2010) on motor learning and mental practice from the CAA-A point of view (see chapters 1.4.3, 1.4.4, and 1.5.1), the present work takes one step further by directly comparing the different types of practice and as such allows for reflections on their particular influence on the motor action system during motor learning. Accordingly, the potential influence of both physical practice (cf. Figure 5.1) and mental practice (cf. Figure 5.2) within the levels of action organization during early stages of motor learning is sketched in the following. The grey circles on the left indicate the involvement of all levels of the motor action system during the learning of a new motor task (cf. Figure 1.1, chapter 1.5.1), while the black circles on the right differentiate the distinct influence of practice type. Specifically, the solid black circles on the right highlight the primary influence of practice type within the motor action system, whereas the dashed black circles on the right mark the secondary influence each practice type may have.

Based on the findings of the present work, learning a motor action by way of mental and physical practice may differ regarding the different levels of action organization. Findings from study 2, for instance, revealed that mental practice alone as well as combined mental and physical practice led to most elaborate representation structures in comparison to an expert structure, while physical practice alone and combined mental and physical practice led to best performance. This indicates that the physical practice component may primarily relate to adaptations on the sensorimotor levels (see Figure 5.1), whereas the mental practice component of the practice regime may primarily relate to adaptations on the representational levels within the motor action system at this particular stage of motor learning (see Figure 5.2).

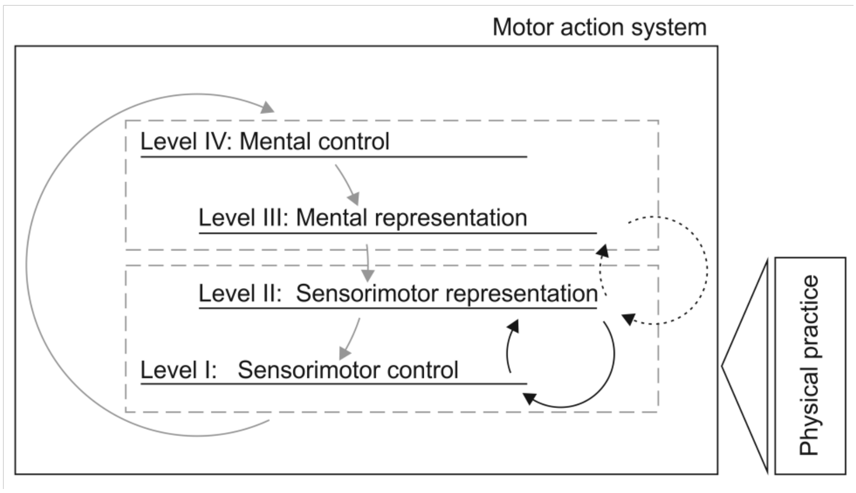


Figure 5.1. The influence of physical practice on the motor action system during early stages of motor learning (adapted and modified from Schack, 2002, p. 59).

Physical practice as an "online" type of practice is suggested to influence the motor action system mainly by way of the sensorimotor system, integrating and storing sensorimotor information (i.e., feedback) that is available from actual movement execution. Specifically, the repeated execution of an action as a sensorimotor experience entails the integration of sensorimotor information into sensorimotor representations and, by way of the latter, into mental representations. More specifically, sensorimotor information is being stored within the sensorimotor representations as a result of physical practice, and as such serves to discriminate and relate concepts by way of dimensioning. This dimensioning results in the structuring of the mental representation, and therefore, in a more and more refined feature-based representation structure. In this sense, the motor action system incrementally stabilizes during motor learning as induced by physical practice, and it does so via the structuring of mental representations based on enriched sensorimotor representations.

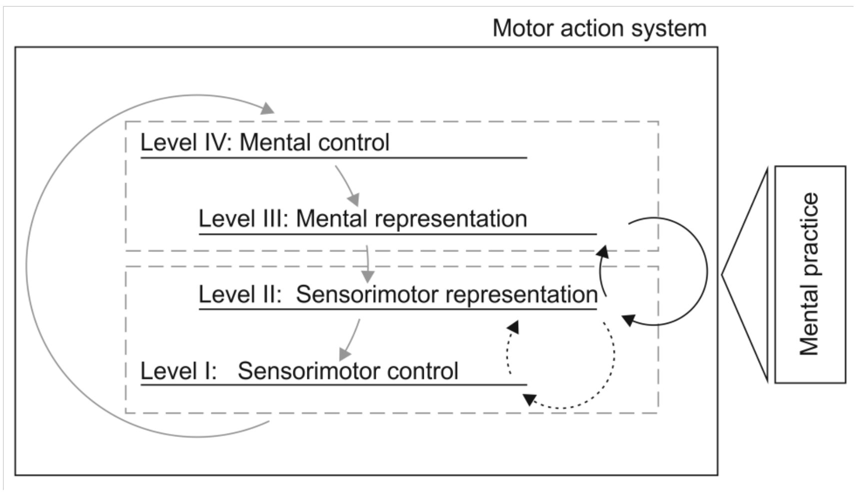


Figure 5.2. The influence of mental practice on the motor action system during early stages of motor learning (adapted and modified from Schack, 2002, p. 59).

Instead, based on the findings of the present work, mental practice as an "offline" type of practice is suggested to influence the motor action system mainly through the representational levels at the interface of the mental and the sensorimotor system, retrieving and re-storing "quasi-sensorimotor information" (i.e., "quasi-feedback") based on the action representation available. Mental practice, in contrast to physical practice, does not involve an actual sensorimotor experience, but the simulation of the latter (i.e., a quasi-sensorimotor experience). As such, the repeated simulation of an action (i.e., mental practice) does not entail the integration of sensorimotor information from the actual experience, but the retrieval and the reintegration of quasi-sensorimotor information from a past experience stored in long-term memory. More specifically, this retrieved and re-stored information serves to reinforce links between sensorimotor and mental representations as a result of mental practice, thereby further relating and differentiating concepts, and finally leading to order formation. In this sense, the motor action system incrementally stabilizes during motor learning as induced by mental practice, and it does so via the structuring of mental representations based on stronger links across representational levels of action organization.

Taken together, based on the findings of the present work, mental practice is suggested to primarily operate on the higher levels within the motor action system, while physical practice may primarily operate on the lower levels within the motor action system. More specifically, the primary influence of mental practice on the motor action system is thought to be centered between the mental and the sensorimotor representational levels, while the primary influence of physical practice on the system is suggested to be centered between the sensorimotor representational and regulatory levels (as indicated by the solid black circles on the right in Figures 5.1 and 5.2). For image generation (i.e., motor imagery and mental practice), the communication between the representational levels is essential, while for generation of the motor output (i.e., motor execution and physical practice) the communication within the sensorimotor system is of primary interest. The direct interaction of the person within his/ her environment with regard to a particular motor task helps to stabilize the perceptual-cognitive system within the human motor action system by allowing sensorimotor patterns to grow and, as a consequence, conceptual structures to evolve (see also Schack, 2002). In contrast, the indirect or simulated interaction strengthens the links between sensorimotor patterns available and the corresponding conceptual structures, stabilizing the perceptual-cognitive system in this way. Thus, learning by way of physical practice is suggested to be closely tied to the feedback available from movement execution leading to a refinement on the sensorimotor levels of action organization, and subsequently transferring to the mental levels of the motor action system (as indicated by the dashed black circle on the right in Figure 5.1). In contrast, learning by way of mental practice is suggested to be closely tied to the quasi-feedback based on the action representation available, and as such is situated on the perceptual-cognitive levels of action organization, reflecting an inner development, potentially transferring to the sensorimotor control level of the motor action system (as indicated by the dashed black circle on the right in Figure 5.2). Although not directly testing for the basic mechanisms, the insights of the present work add to the picture of potential basic mechanisms that underlie each type of practice, an issue which is still being highly debated (e.g., Annett, 1995b; Cumming & Williams, 2012; Glover & Dixon, 2013; Jackson, Lafleur, Malouin, Richards, & Doyon, 2001; Munzert, Zentgraf, Stark, & Vaitl, 2008; Murphy, Nordin, & Cumming, 2008). However, additional research is needed to further test the model presented and to foster the statements and hypotheses derived from the present findings.

As a side note, it is conceivable that a perceptual-cognitive, representation-based view on mental practice as presented in the present work may help explain ambiguous findings in the field, for instance regarding the effectiveness of mental practice. So far, from the performance point of view, mental practice has proven to be effective, although not as effective as physical practice (e.g., Driskell et al., 1994). However, there are as well studies showing that mental practice can be superior to physical practice in enhancing performance (e.g., Healy & Wohldmann, 2012; Wohldmann et al., 2007; Wohldmann, Healy, & Bourne, 2008). Thus, to some degree, results on the influence of mental practice on the performance of a motor task remain ambiguous, having researchers led to the conclusion that the influence of both practice types and their relationship are of complex nature, with type of task being one major factor of influence (e.g., Driskell et al., 1994). For instance, while Wohldmann et al. (2008) reported mental practice to be superior to physical practice in a task with high "cognitive" demands (i.e., typing four digit numbers), Reiser, Büsch, & Munzert (2011) reported physical practice to be superior to mental practice in tasks with low cognitive, and higher "motor" demands (i.e., bench pressing; leg pressing, triceps extension, and calf raising). In addition, related to this is the discussion on the cognitive-motor hypothesis, stating that cognitive tasks may benefit more from mental practice than motor tasks (e.g., Ryans & Simons, 1981, 1983). Approaching mental practice and physical practice effects from a hierarchical point of view, our findings add to this discussion in the way that, within a motor task, it is primarily the perceptual-cognitive levels of action that seems to be promoted by mental practice. In this sense, the findings of the present work can be regarded as an extension of the cognitive-motor hypothesis in mental practice research (for details, see chapter 3.4).

In addition to the CAA-A related elaborations above, particular examples of related research addressing mental and physical practice along these lines will be described and discussed in the light of the findings of the present work: first, a hierarchical explanation for mental and physical practice effects will be addressed, drawing back on elaborations by Mackay (1981). Second, and more specifically, the role of feedback in explaining mental and physical practice effects will be elaborated on in the light of a study conducted by Wulf, Horstmann and Choi (1995). Third, and finally, mental and physical practice will be approached by way of memory accounts, as has recently been done by Raisbeck, Wyatt and Shea (2012).

Ad 1, from our findings, it seems that both types of practice operate through and find expression on different levels of the motor action system, and thus influence subsequent performance differently. Specifically, the findings of the present work suggest that mental practice primarily promotes the perceptual-cognitive adaptation within the motor action system.

In the same veins, Mackay (1981) approached mental practice and its effects from a hierarchical view. Based on findings of a speech production experiment, thereby examining the influence of mental and physical practice on the performance and the transfer of a speech production task, the author developed a hierarchical theory of behavior organization. According to this theory, higher level mental nodes are being activated during mental practice, thereby priming lower level muscle movement nodes. As a consequence, in the case of skilled action (i.e., the muscle movement nodes exist) mental practice is suggested to be effective, because the activation of mental nodes results in the priming of muscle movement nodes (i.e., *the muscle priming* *phenomenon*; Mackay, 1981). Instead, in the case of unskilled action, (i.e., the muscle movement nodes do not exist) mental practice is suggested to be not effective, because the activation of mental nodes cannot result in any muscle priming. Accordingly, motor performance can be facilitated by mental practice in individuals holding an advanced level of skill, but not in individuals being new to a task. Thus, from this view, mental practice effects are restricted to skilled action.

Interestingly, what was not addressed explicitly by Mackay (1981) is the question whether, in the case of unskilled action and thus during early skill acquisition, mental practice has any influence on higher levels within the action system, despite the lack of improvements in motor performance. Specifically, Mackay (1981) did not elaborate on whether mental practice may influence the mental nodes and their formation even if no muscle movement nodes exist that may allow for subsequent changes in performance. Similarly, according to the hierarchical view of the CAA-A, the motor action system is comprised of a higher mental and a lower sensorimotor system. Along these lines, and as an extension of Mackay's elaborations, mental practice can be considered as inducing changes on representational levels within the motor action system, although not necessarily and immediately resulting in any overt changes on the performance of a motor action (cf. Figure 5.2).

Ad 2, mental and physical practice obviously differ in terms of the feedback available during the execution and the imagery of an action. This distinction has researchers led to differentiate these two types of practice into (physical) "online" and (mental) "offline" practice (cf. Beilock & Lyons, 2009). First, and foremost, physical practice is concerned with the individual practicing a task in his or her environment, and therefore experiencing an actual motor action. While doing so, actual stimuli are present, both from the environment and from the individual, and the movement is being produced within this reality, including actual sensorimotor feedback. Instead, mental practice is concerned with the image of the individual practicing a task in his or her environment, with the image depending on the individual's imagery ability and various other factors. As such, the experience can be regarded a quasi-experience of an actual motor action, being a vicarious, a representative, a non-actual experience.

During motor imagery, therefore, no actual stimuli and no feedback from actual motor execution are present. Thus, by its very nature, mental practice is an offline process primarily fed by and based on information resulting from a quasi-experience within a non-actual situation, whereas physical practice is an online process primarily fed by and based on information arising from the actual situation and the feedback perceived therein (for more details, see above).

Addressing the idea that feedback may account for the differences in mental and physical practice and their effect on the motor action system, Wulf et al. (1995) approached the basic mechanisms of both types of practice with a particular focus on the availability of feedback during mental and physical practice. Motivated by the intriguing finding that a combination of mental and physical practice can be more effective than physical practice alone, Wulf et al. (1995) noted that, so far, this phenomenon cannot be explained by any existing theory. Accordingly, the authors argued that this combination of mental and physical practice may prove beneficial for the following reason: as the individual does not receive and does not have to integrate feedback after each trial (i.e., in the case of mental practice trials during combined practice, no feedback is available and thus feedback does not have to be processed), the development of a stable movement representation may be promoted. Instead, when receiving feedback after each trial (i.e., in the case of physical practice) permanent correction processes may prevent the individual from developing such a movement representation. Thus, the authors argued that feedback would be the main distinguishing factor of both practice types, and that mental practice may work like physical practice without feedback. Accordingly, they examined the question whether mental practice (i.e., MP) and physical practice without information feedback (i.e., IF) would similarly influence the learning of a motor action. Three groups practiced a golf putting task either with all trials followed by feedback (100% IF), with half of the trials substituted by either no feedback following the execution of the putt (50% IF) or imagining the putt without actually executing it (50% MP). It was predicted that if mental practice worked like physical practice without information feedback then both 50% groups (IF and MP) would show a similar amount of motor learning (here:

improved performance during retention-test) and more so compared to the 100% IF group. Contrary to the authors' predictions, the 50% IF group showed better learning compared to the 50% MP and the 100% IF groups when there was no feedback available. In addition, when there was feedback available, all three groups performed equally after the retention interval. Based on their findings on the behavioral level, the authors concluded that feedback is not the only factor distinguishing mental and physical practice. More importantly, the authors ended up stating that

> "it still remains unclear why combined physical and mental practice can enhance learning relative to physical practice alone. Determining what are the exact underlying mechanisms of MP remains a challenge for future research" (Wulf et al., 1995, p. 266).

Importantly, Wulf et al. (1995) approach motor learning from the motor output level, thereby employing performance as an indicator of learning. Specifically, in their study, each of the three groups had learned to a similar degree in the sense that the groups had reached a comparable level of performance after the retention interval when being provided with feedback. Thus, this study shows that a lack of feedback during some of the trials does not seem to lead to differences in performance, neither to increases nor to decreases. What this study does not show is the degree to which representations change.

To this extent, the findings fit well with the findings of the present work such that a combination of mental and physical practice leads to similar levels of performance in golf putting compared to physical practice alone. What the findings of the present work elicited in addition is that a combination of both practice types led to differential effects on a perceptual-cognitive level. Following up on the idea of Wulf et al. (1995), it would be interesting to have a closer look at the perceptual-cognitive adaptations, and thus the development of mental representation structure, during learning by physical practice with feedback, physical practice without feedback and mental practice, and whether it develops differently depending on the feedback available (cf. Figures 5.1 and 5.2). In cases without feedback from actual movement execution during physical practice, processing of information might be deeper, leading to more elaborate mental representation structure, and thus in this way promoting order formation in memory (for a discussion on levels of processing, see below).

Ad 3, a potential memory-based account for the differences in mental and physical practice will be discussed in the light of more recent work by Raisbeck et al. (2012). In doubting that mental practice has any influence on motor performance at all, Raisbeck et al. (2012) approached mental and physical practice by focusing on potential differences in processing structures which underlie mental and physical practice, and which may cause the differential effects that the two types of practice have on the performance of a motor task. Specifically, Raisbeck et al. (2012) investigated the influence of mental and physical practice on response initiation and execution of a key pressing task, thereby employing a transfer paradigm. Participants practiced under one of four conditions: mental-mental practice, physical-physical practice, mental-physical practice, physical-mental practice. To explain, participants in the combined groups either switched from mental to physical practice or vice versa during acquisition phase. In doing so, Raisbeck et al. (2012) aimed to approach the underlying mechanisms of mental and physical practice by showing that a switch from one type to another causes interferences and leads to changes in performance, and in this case to changes in response times. The authors found execution times to become longer when switching from physical to mental practice, whereas execution times became shorter when switching from mental to physical practice. Based on their finding of an interaction resulting from the switch between the two types of practice, the authors concluded that different task representations may have developed during each type of practice, and that the processes of each practice type were different for each task representation. As a consequence, the authors suggested a memory-based account, separated into two processes for mental and physical practice effects. Specifically, the degree of effort needed for response execution served as an explanation for the differences found in response times between mental and physical practice. Accordingly, mental practice was suggested to be deliberate and to require effortful processing during response execution, whereas physical practice was suggested to be automatic and to require less effortful processing.

In the realm of the CAA-A and the perceptual-cognitive hypothesis of mental practice, one may re-interpret the findings reported by Raisbeck et al. (2012) in terms of adaptations on different levels within the hierarchy of action organization. Specifically, the switch between the two types of practice and the resulting changes in response times may reflect differences in mental and physical practice such that they operate on different levels within the motor action system (cf. Figures 5.1 and 5.2). If learning by mental practice is memory induced thereby primarily affecting the representational levels, and if learning by physical practice is feedback induced and thereby primarily affecting the sensorimotor levels, then it is not surprising that transfer leads to interference as found by Raisbeck et al. (2012).

In the same veins, mental practice has been described as being more effortful (e.g., Willingham, 1998). The issue of effort together with reflections on memory directly relate to the groundbreaking work of Craik and Lockart (1972) in the field of memory research. Originating in the field of verbal learning, their general idea was to view memory in terms of levels of processing. Accordingly, memory is approached by processing as opposed to entities. Along these lines, the degree to which something can be remembered depends on the depth of processing that had occurred during initial encoding. In his update on the original ideas, Craik (2002) revisits the levels of processing idea, thereby expanding the idea to hierarchical models on cognition, suggesting a hierarchical view of cognitive representations with higher, more abstract, and lower, more specific representational levels. In this revisit, Craik (2002) concludes with the words,

> "I have seen no evidence against the proposition that the memory trace reflects those processes carried out primarily for the purposes of perception and comprehension, and that more meaningful processing is usually associated with higher levels of recollection." (Craik, 2002, p. 316)

Mental practice, in this sense, may be associated with a greater depth of processing, while physical practice, in turn, may relate to a lower depth of processing (cf. Figures 5.1 and 5.2), resulting in more developed representations for mental practice.

Along these lines, one may even speculate on the direction of processing within the hierarchy of action organization as induced by both mental and physical practice (e.g., Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004). It may be the case that changes within the motor action system as induced by physical practice may transfer from the sensorimotor to the mental levels over time (i.e., bottom-up changes), while changes within the motor action system as induced by mental practice may transfer from the mental to the sensorimotor levels over time (i.e., top-down changes). In other words, changes on the mental levels of the motor action system caused by mental practice may subsequently impact the sensorimotor system. For physical practice, on the other hand, changes on the sensorimotor levels of the motor action system may, in turn, have some impact on the mental system (cf. Figures 5.1 and 5.2). However, this idea certainly warrants further considerations and investigations.

Taken together, the findings of the present work support the notion that mental and physical practice may operate through and find expression on different levels within the motor action system. Specifically, the findings indicate that mental practice is particularly associated with perceptual-cognitive changes within the motor action system during early skill acquisition. From this, it seems that the basic mechanisms of mental and physical practice may be differentiated in the way that they are based on "offline" and "online" information. The influence of both practice types may differ to the degree that they are memory-based (i.e., based on "quasi-feedback" from the action representation available) or feedback-based (i.e., based on actual feedback from motor execution). As has been discussed in the realm of the CAA-A (cf. Figures 5.1 and 5.2) and related work providing memory-based and feedback-based accounts for both mental and physical practice (see above), one might presume that changes within the motor action system in the case of physical practice are primarily feedback-based, taking place within the sensorimotor system. Instead, in the case of mental practice adaptations may primarily be memory-based, taking place between the representational levels of the sensorimotor and the mental system. Although the present work provides some support in this direction, these straightforward presumptions certainly warrant further investigation and experimental testing.

Interestingly, although researchers generally agree upon the different natures of the two types of practice and the different magnitudes of effect on the performance of a motor action that both types of practice have, little is known about the differential (or similar, respectively) mechanisms of both practice types within the motor action system to this day. Compared to the exploration of the influence that each type of practice has on performance, relatively few theories exist that address the basic mechanisms of both mental and physical practice, thereby trying to answer questions on the differential processes taking place within the motor action system (for details, see chapter 1.2.2). In fact, the principle of functional equivalence and the simulation theory, being the most influential among recent approaches to describing and explaining processes during overt and covert stages of action (and thus during physical and mental practice), have provoked an orientation toward potential similarities between and shared mechanisms of the two stages of action. Specifically, in aiming at understanding the basic mechanisms from a neurocognitive point of view, both the principle of functional equivalence and the simulation theory have stimulated a tremendous body of research (see chapter 1.2.2.3). From this, both stages of action seem to adhere to similar principles, and in this sense are to be treated as functionally equivalent. However, and what is important to note, since the appearance of the principle of functional equivalence and later the simulation theory of action, surprisingly little attention has been devoted to the potential differences in basic mechanisms that may exist between the imagery and the execution of an action, and between mental and physical practice, respectively.

More recently, however, research interest in approaching the execution and the imagery of an action, and physical and mental practice respectively, by looking more closely at what differentiates them from one another has re-emerged (e.g., Wakefield, Smith, Moran, & Holmes, 2013). Although, strictly speaking, the findings of the present work do not allow for conclusions regarding the underlying mechanisms of both types of practice, results at least point toward differential effects of both types of practice, which resulted in a discussion of potential reasons leading to these differences. In order to gain a thorough picture of how the imagined and the actual execution of an action influence the motor action system during the learning of a motor action, it will be valuable to focus on both the similarities and the differences between these two stages of action. It seems crucial to find out what mental and physical practice have in common and, at the same time, what the distinct contribution of each during motor skill acquisition is.

5.3 Limitations and prospects

The present work provides novel insights into motor learning as induced by mental and physical practice by shedding light on the perceptual-cognitive changes that take place within the human motor action system during early motor skill acquisition. Although the main research questions have been answered in the realm of the present work, numerous questions related to the present work remain unanswered. Further research is therefore warranted to gain a more detailed understanding of motor learning and mental practice from a perceptual-cognitive, representation-based point of view. In the following, limitations of the present work and prospects for future work in the area of basic and applied research are being presented.

From the CAA-A perspective, several issues directly related to the present work remain to be answered. First, the focus in examining the underlying mental representation of complex action laid on its structure (i.e., the relation and the grouping of BACs) and how the structure changes over time. Thus, while we have learnt about the structuring of mental representation in the present work, the dimensioning of mental representation and its changes as a result of mental and physical practice so far have not been addressed (for details on the dimensioning of mental representation, see chapter 1.4.2). As the structure of mental representation of complex action is thought to be feature-based, it may be valuable to have a closer look at the types of features (i.e., functional and sensory ones), the amount of features, the distribution of features across concepts, and how these features contribute to the structuring of mental representation. To investigate the dimensioning of mental representations may shed further light on the differential influence that physical and mental practice have on the motor action system (see also chapter 5.2.2; cf. Figures 5.1 and 5.2).

Second, as the organization of motor action is thought to take place within two systems (i.e., the mental and the sensorimotor system) and thus on several levels within the motor action system, it seems valuable to further try to uncover the processes within the hierarchy of action organization. From our research, the (covert) perceptual-cognitive adaptations do not seem to directly result in (overt) behavioral adaptations in terms of motor performance. However, it is conceivable that after a longer period of time, as learning progresses, the perceptual-cognitive adaptations transfer to adaptations in motor performance, and that, in turn, adaptations in motor performance transfer to perceptual-cognitive adaptations. In other words, it is conceivable that the adaptations as induced by physical practice cause bottom-up changes, while the adaptations as induced by mental practice cause top-down changes within the motor action system. Thus, it seems valuable to further examine how the changes on the different levels of action organization relate to one another, whether they transfer more or less directly or whether this transfer is mediated by distinct factors (e.g., amount of practice, skill level, consolidation).

Third, and related to this, to further approach the relationship between representation and performance and its changes over time will help to shed further light on how motor action is organized and how this organization changes with practice. Therefore, it seems valuable to have a closer look at the motor action during motor learning, using a combination of biomechanical, physiological, and perceptual-cognitive methods. First steps in this direction have been taken by Heinen (2005), and more recently by Land, Volchenkov, Bläsing, and Schack (2013), both examining the overlap of cognitive and biomechanical aspects of motor action. While motor performance has been approached by its outcome in the present work, a more detailed understanding of the changes taking place within the sensorimotor system, and their relation to the mental representation will be gained by approaching motor performance more thoroughly. Specifically, approaching motor performance not only by its outcome (i.e., the result of movement execution), but also by its quality (i.e., the process of movement execution itself), and as well by even more direct measures such as physiological activity in the muscles (i.e., EMG) that are involved in that particular motor action, seems promising in learning more about the interplay of the sensorimotor and the mental system during motor action organization.

Fourth, the present work has taken an initial step in direction of examining the functional links between mental representation and perception during learning, with a particular focus on the quiet eye. However, future research is needed to further explore the relation of perception and mental representation and their change over the course of practicing a motor action. Related to this, it will be interesting to further explore the influence of mental and physical practice on attention (e.g., Foerster, 2011; Heinen, Mandry, Vinken, & Nicolaus, 2014; Heinen, Vinken, & Fink, 2011) and the mental representation of a complex action (e.g., Essig, Janelle, Borgo, & Koester, 2014; Tenenbaum, & Gershgoren, 2014; Weigelt, Schack, & Kunde, 2007).

Going beyond the scope of the CAA-A, it seems noteworthy that, with the present work only a very short part of the entire process of learning a complex motor action was depicted, namely early skill acquisition. The three learning studies exclusively relate to initial changes within the motor action system during early phases of motor learning. Specifically, perceptual-cognitive changes after the first few days of practice (here: 3 days; i.e., relatively small amount of practice sessions), and after only few days of no practice (here: 3 days; i.e., relatively short length of retention interval) have been investigated. Accordingly, a significant, but still miniature and for sure incomplete picture of the processes taking place within the motor action system during motor learning and mental practice has been drawn. Moreover, the learning of one particular complex action (here: the golf putt; i.e., no transfer from one to another skill) has been investigated. In respect thereof, it seems valuable to further pursue this line of research by investigating the learning process in more detail such that the retention and the transfer of learning will be explored from a representational viewpoint. To investigate long-term retention will provide further insights into the persistence (i.e., retention) and the loss (i.e., forgetting) of mental representation of complex action. In addition, to examine the degree of transfer from the learned motor action to another motor action, and its relation to one's underlying representation of the action, will help to gain further insights into the adapting motor action system.

Furthermore, mental and physical practice were introduced in their most simple versions. In the three learning studies, participants practiced the putt by repeatedly rehearsing it either mentally or physically (or both). Variations in the practice regimes were not provided and therefore research has yet to investigate the development of mental representations in the light of different practice conditions. Specifically, the conditions of practice and their effect on the learning of a motor action have been highly investigated in terms of (overt) performance (e.g. variability of practice: e.g., Shea & Kohl, 1990; variability of physical and mental practice: e.g., Gabriele, Hall, & Lee, 1989), but not with regard to the (covert) perceptual-cognitive aspects of motor action. Accordingly, with respect to the effectiveness of learning, an interesting extension of the present work would be to investigate the influence of different conditions of practice on mental representation development. A first step in this direction has been taken by Land et al. (2014), demonstrating the influence of type of instruction (here: internal vs. external focus of attention during golf putting) on the rate of representation development during early skill acquisition. Specifically, in their study, an external focus of attention during learning led to greater putting accuracy and consistency as well as more developed representation structures of the putt compared to an internal focus of attention. Further investigating which conditions lead to most developed representation structures, and whether this is complementary to the performance of a motor action, will shed further light on motor learning. More general, having a closer look at practice conditions by investigating representational networks of complex action and their development may help to solve some of the remaining questions in the field.

In the present work, motor learning through mental and physical practice have been approached from a perceptual-cognitive point of view. To take a neurophysiological perspective and to investigate neurophysiological correlates of perceptual-cognitive changes within the motor action system may significantly add to the findings of the present work. For instance, Zhang et al. (2014) recently examined functional connectivity within the brain over the course of learning as induced by mental practice. From their findings of changes in resting state functional connectivity in sensory and cognitive resting state networks, the authors drew conclusions about the formation of action representation. While their conclusion regarding the representation of motor action has been drawn indirectly from neurophysiological evidence, directly addressing representations by examining the change of mental representation structure by way of the SDA-M will foster evidence on the cognitive adaptation in addition to the neural adaptation as reported by Zhang et al. (2014). Accordingly, a combination of behavioral, neurophysiological, and cognitive approaches, thereby examining changes in overt performance and in covert neural and cognitive representations, and thus considering the behavior, the brain and the mind during motor action, may contribute to draw a more thorough picture of changes within the motor action system during motor learning. It is likely that such an interdisciplinary approach using various methods from various disciplines will help to grow our knowledge and to advance our understanding of the human action system.

Switching from the theoretical to a more applied perspective, it would be of great interest to learn more about the effects of representation-based learning and coaching. From the learning point of view, representation-based learning in comparison to traditional learning, which does not directly address the individual's representation of an action, seems promising as a future learning strategy (e.g., Heinen & Schack, 2004; Heinen & Schwaiger, 2002; Heinen, Schwaiger, & Schack, 2002; Schack & Bar-Eli, 2007; Schack & Hackfort, 2007). It will be interesting to further investigate the influence of representation-based learning in comparison to normative learning across different skill levels, thereby investigating the question whether representation-based learning is as effective as or even more effective than traditional strategies when working with athletes. Another idea, from the coaching point of view, may be to investigate interactions that are based on traditional, representation-blind communication between the coach and the athlete and interactions that are based on more objective analyses of the athlete's representation of a given motor action.

Directly related to the idea of representation-based learning in general is to individualize mental practice (e.g., Williams, Cooley, Newell, Weibull, & Cumming, 2013) such that the image to be rehearsed and the instructions given are based on the individual's mental representation, as measured via SDA-M (i.e., mental training based on mental representation (MTMR); Schack & Bar-Eli, 2007; Schack et al., 2014; Schack & Hackfort, 2007; Schack & Heinen, 2000). A step in this direction has been taken by Velentzas (2010), investigating the influence of individualized compared to non-individualized mental practice on spike performance in highly-skilled volleyball players. Mental practice of the spike was either based on individualized (i.e., representation-based) imagery scripts or on generic (i.e., not representation-based) imagery scripts. Specifically, generic scripts were based on general information on the technique of the volleyball spike, whereas individualized scripts were based on each individual's representation of the spike. According to the results, those players practicing with individualized imagery scripts elicited better performance after practice compared to the ones practicing with generic scripts. Thus, findings revealed that those volleyball players provided with representation-based imagery scripts profited more from mental practice compared to those who practice mentally in a non-representation-based fashion. From this, the author concluded that mental practice is more effective when it is based on and adapted to the individual's representation of the complex motor action to be practiced compared to standardized mental practice.

Finally, representation-based learning and coaching in the realm of either mental or physical practice may also be transferred onto technical platforms such as robots and virtual agents (e.g., Schack & Ritter, 2009, 2013; Schack, Bertollo, Koester, Maycock, & Essig, 2014). Specifically, as a supplement to the traditional human-human interaction between the coach and her/ his athlete, human-robot or human-virtual agent interaction may prove fruitful in situations during which the coach is not present, or in situations that deserve intensive one-to-one coaching that cannot be accomplished by the coach without neglecting the rest of the team. Therefore, systems may be built that are able to measure the athlete's representation of an action, to analyze it in comparison to the representation of an expert, to detect movement errors based on this analysis, and finally to instruct the athlete accordingly. To date, initial ideas in direction of an intelligent coaching space have arisen (e.g., De Kok, Hough, Frank, Schlangen, & Kopp, 2014), whereas it remains a future challenge to build a coaching space, in which the coachee experiences a comfortable, motivating, and informative learning environment, that significantly adds to traditional ways of learning, and thus results in an ideal supplement to everyday work in human-human interaction in our gyms.

Taken together, although the findings of the present work make a distinct contribution to recent research in motor learning in general and mental practice in particular, many of the questions arising during the planning, conducting, analyzing, and writing of the present work remain to be investigated. In fact, the present work has led to a considerable collection of questions, growing further and inviting to take numerous further steps on the way to gain a deeper, more sophisticated understanding of the complex and intriguing human motor action systems.

5.4 Conclusion

To date, a strikingly large body of research exists in the area of motor learning (see chapter 1.1). Similar to the field of motor learning, a wealth of research has been conducted and tremendous progress has been made in the field of mental practice in the last few decades (see chapter 1.2). Conclusions about motor learning as induced by mental and physical practice are usually inferred from changes in motor performance or changes in brain activation (see chapters 1.3.1 and 1.5.1). As previously elaborated on in more detail, the complexity of the motor action system, with perceptual-cognitive representations guiding motor action and changing over the course of motor learning, most likely cannot be grasped by focusing on either behavioral or neural changes taking place during the learning of a complex action. Rather, it is essential to go beyond behavioral or neural changes, and to directly address the representation of an action if the aim is to understand the adapting motor action system during motor learning from within. The present work advances in this direction by approaching motor learning through mental and physical practice from a representation-based perspective, highlighting the perceptual-cognitive adaptations within the motor action system during motor learning, and focusing on the functional role of mental representations of complex action.

From the findings of the present work, practice is associated with both behavioral adaptations (in terms of motor performance) and perceptual-cognitive adaptations (in terms of mental representation structure and gaze behavior) (see chapter 5.2.1). Moreover, mental and physical practice differ in their influence on the motor action system with respect to perceptual-cognitive and behavioral adaptations (see chapter 5.2.2). Study 1, 2, and 3 clearly demonstrate that performance improvements go along with functional changes in mental representation structure when practicing a motor action. Accordingly, motor learning can be viewed in terms of a development of representation structures, and thus as order formation in long-term memory. Study 2 and 3 additionally indicate that mental practice promotes this development even more than physical practice does. Practice incorporating a mental component (i.e., imagining the motor action without executing it at the same time) led to most elaborate representation structures and most elaborate gaze behavior in the present work. Notably, these adaptations did not transfer one-to-one to the motor output level, pointing to an inner refinement within the motor action system that is not necessarily observable in terms of motor performance. From this, mental practice seems to particularly promote the perceptual-cognitive components of motor action within the motor action system.

Given that, as found within the scope of the present work, functional changes in mental representation and gaze behavior do not necessarily transfer one-to-one to changes in overt motor performance (i.e., the motor action system changes covertly in terms of perceptual-cognitive adaptations, but not overtly in terms of behavioral adaptations), it seems crucial to consider motor learning as being more than just a reflection on the surface of the human motor action system, as measured in terms of performance improvements. Motor learning does not have to be necessarily reflected in both covert and overt changes. Essentially, motor learning takes place on different (covert and overt) levels within the motor action system. In this sense, apprehending that learning does not necessarily have to become visible in terms of behavioral adaptations, and that it can take place solely internally, thus become evident as perceptual-cognitive adaptations only, may contribute to solve some of the remaining questions in our area. It is therefore unlikely that motor learning as induced by mental and physical practice can adequately be understood by taking either a behavioral or a neural perspective. Rather, when it comes to understanding the intelligence and the complexity of learning within the human motor action system researchers must take a perceptual-cognitive perspective, thereby including and directly addressing the functional role of representations in long-term memory. From the findings of the present work, it seems therefore essential to approach motor learning and the influence of mental or physical or any other type of practice on the motor action system, from a perceptual-cognitive, representation-based perspective in future studies.

To widen the view on the adapting motor action system by investigating changes on different levels within the motor action system, as has been done in the present work, seems to prove valuable in elucidating the phenomenon of motor learning in general and the one of mental practice in particular. Further approaching the effects of mental and physical practice in this way, both in isolation and in comparison to one another, may even help to uncover potential mechanisms, and to develop a comprehensive theory of mental and physical practice. More generally speaking, it seems crucial to combine perspectives, theories and measures from movement science, cognitive psychology, and neuroscience, to gain a more holistic picture of the adapting and learning human motor action system. Similar to investigating changes in the brain by way of neurophysiological methods, it seems crucial to examine changes in the mind by way of cognitive methods. Moreover, combining behavioral, neuroscientific and cognitive approaches, thereby examining changes in overt performance and in underlying neural and cognitive representations may strongly contribute to draw a thorough picture of changes within the motor action system during mental and physical practice.

Taken together, the aim of the present work was to take one step forward in advancing our understanding of learning a complex action by mental and physical practice. Specifically, the present work shed further light on motor learning in general and mental practice in particular from a perceptual-cognitive, representation-based perspective. By approaching the motor action system as one entity of various levels of action organization, thereby focusing on perceptual-cognitive adaptations, and on the development of mental representation in particular, the present work provided some empirical support for and a better understanding of motor learning and the influence of mental and physical practice on the motor action system from within.

REFERENCES

Abrahamsen, A., & Bechtel, W. (2012). History and core themes. In K. Frankish & W. Ramsey (Eds.), *Cambridge Handbook of Cognitive Science* (pp. 9-28). Cambridge: Cambridge University Press.

Ach, N. (1921). *Untersuchungen zur Psychologie und Philosophie. Über die Begriffsbildung. Eine experimentelle Untersuchung*. Bamberg: C. C. Buchners.

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3*, 111-150.

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin, 101*, 41-74.

Allami, N., Brovelli, A., Hamzaoui, E. M., Regragui, F., Paulignan, Y., & Boussaoud, D. (2014). Neurophysiological correlates of visuo-motor learning through mental and physical practice. *Neuropsychologia, 55*, 6-14.

Allard, F., & Burnett, N. (1985). Skill in sport. *Canadian Journal of Psychology, 39*, 294-312.

Allard, F., Graham, S., & Paarsalu, M. E. (1980). Perception in sport: basketball. *Journal of Sport Psychology, 2*, 14-21.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89*, 369-406.

Anderson, J. R. (1993). *Rules of mind*. Hillsdale: Erlbaum.

Anderson, J. R. (1995). *Learning and memory*. New York: Wiley.

Annett, J. (1995a). Motor imagery: Perception or action? *Neuropsychologia, 33*, 1395-1417.

Annett, J. (1995b). On knowing how to do things: A theory of motor imagery. *Cognitive Brain Research, 3*, 65-69.

Anochin, P. K. (1967). *Das funktionelle System als Grundlage der physiologischen Architektur des Verhaltensaktes*. Jena: Gustav Fischer.

Bartlett, F. (1932). *Remembering: A study in Experimental and Social Psychology*. Cambridge: Cambridge University Press.

Beek, P. J., Schmidt, R. C., Morris, A. W., Sim, M.-Y., and Turvey, M. T. (1995). Linear and nonlinear stiffness and friction in biological rhythmic movements. *Biological Cybernetics, 73*, 499-507.

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: what governs choking under pressure? *Journal of Experimental Psychology: General, 130*, 701-725.

Beilock, S. L., & Lyons, I. M. (2009). Expertise and the mental simulation of action. In K. D. Markman, W. M. P. Klein, & J. A. Suhr (Eds.), *Handbook of imagination and mental simulation* (pp. 21-34). New York: Psychology Press.

Beilock, S. L., Wierenga, S. A., & Carr, T. H. (2002). Expertise, attention, and memory in sensorimotor skill execution: Impact of novel task constraints on dual-task performance and episodic memory. The *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 55*, 1211-1240.

Beilock, S. L., Wierenga, S. A., & Carr, T. H. (2003). Memory and expertise. In J. L. Starkes, & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise* (pp. 295-320). Champaign: Human KineticsBernstein, N. A. (1947). *O postrojenii dvizenij*. Mozkva: Medgiz.

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

Bernstein, N. A. (1971). Bewegungskontrolle. In T. Kussmann & H. Kölling (Hrsg.), *Biologie und Verhalten* (S. 146-172). Bern: Huber.

Bernstein, N. A. (1996). *Die Entwicklung der Bewegungsfertigkeiten*. Leipzig: IAT Eigenverlag.

Blaser, P., Stucke, K., Körndle, H., & Narciss, S. (2000). *Auswirkungen eines Leistungstrainings im Brustschwimmen auf den Zusammenhang von Bewegungsrepräsentation und Bewegungsausführung*. Köln: Strauß.

Bläsing, B. (2010). The dancer's memory: Expertise and cognitive structures in dance. In B. Bläsing, M. Puttke, & T. Schack (Eds.), *The neurocognition of dance* (pp. 75-98). London: Psychology Press.

Bläsing, B., Schack, T., & Brugger, P. (2010). The functional architecture of the human body: assessing body representation by sorting body parts and activities. *Experimental Brain Research, 203*, 119-129.

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

Boschker, M. S. J. (2001). *Action-based imagery: On the nature of mentally imagined motor actions* (doctoral dissertation). Vrije Universiteit, Amsterdam.

Boschker, M. S. J., Bakker, F. C., & Michaels, C. F. (2002). Effect of mental imagery on realizing affordances. *The Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology, 55*, 775-792.

Braun, S. M., Beurskens, A. J. H. M., Schack, T., Marcellis, R. G., Oti, K. C., Schols, J. M., & Wade, D. T. (2007). Is it possible to use the SDA-M to investigate representations of motor actions in stroke patients? *Clinical Rehabilitation, 21*, 822-832.

Campbell, M. J., & Moran, A. P. (2014). There is more to green reading than meets the eye! Exploring the gaze behaviours of expert golfers on a virtual golf putting task. *Cognitive Processing, 15*, 363-372.

Carpenter, C. B. (1894). *Principles of mental physiology*. New York: Appleton.

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

Chi, M. T. H., & Rees, E. T. (1983). A learning framework for development. *Contributions to Human Development, 9*, 71-107.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*, 155-159.

Corbin, C. (1967a). The effects of covert rehearsal on the development of a complex motor skill. *The Journal of General Psychology, 76*, 143-150.

Corbin, C. (1967b). Effects of mental practice on skill development after controlled practice. *Research Quarterly, 38*, 534-538.

Craik, F. I. M. (2002). Levels of processing: Past, present... and future? *Memory, 10*, 305-318.

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*, 671-684.

Cumming, J., & Williams, S. E. (2012). The role of imagery in performance. In S. M. Murphy (Ed.), *The Oxford handbook of sport and performance psychology* (pp. 213-232). New York: Oxford University Press.

Davids, K., Button, C., & Bennett, S. (2008). *Dynamics of skill acquistition: A constraint- led approach*. Champaign: Human Kinetics.

Davids, K., Renshaw, I., Pinder, R., Adaújo, D., & Vilar, L. (2012). Principles of motor learning in ecological dynamics: A comment on functions of learning and the acquisition of motor skills (with reference to sport). *The Open Sports Sciences Journal, 5*, 113-117.

Dayan, E., & Cohen, L. G. (2011). Neuroplasticity subserving motor skill learning. *Neuron, 72*, 443-454.

De Groot, A. D. (1965). *Thought and choice in chess*. The Hague: Mouton.

De Kleijn, R., Kachergis, G., & Hommel, B. (2014). Everyday robotic action: Lessons from human action control. *Frontiers in Human Neuroscience, 8*, Article 13.

De Kok, I., Hough, J., Frank, C., Schlangen, D., & Kopp, S. (2014, in press). Dialogue structure of coaching sessions. *Proceedings of the 18th SemDial Workshop on the Semantics and Pragmatics of Dialogue (DialWatt)*. Herriot-Watt University, Edinburgh.

Di Nuovo, A. G., Marocco, D., Di Nuovo, S., & Cangelosi, A. (2013). Autonomous learning in humanoid robotics through mental imagery. *Neural Networks, 41*, 147-155.

Decety, J. (1996). Do imagined and executed actions share the same neural substrate? *Cognitive Brain Research, 3*, 87-93.

Decety, J. (2002). Is there such a thing as functional equivalence between imagined, observed and executed action? In A. N. Meltzoff & W. Prinz (Eds.), *The imitative mind: Development, evolution, and brain bases* (pp. 291-310). Cambridge: Cambridge University Press.

Doyon, J., & Benali, H. (2005). Reorganization and plasticity in the adult brain during learning of motor skills. *Current Opinion in Neurobiology, 15*, 161-167.

Doyon, J., & Ungerleider, L. G. (2002). Functional anatomy of motor skill learning. In L. R. Squire and D. L. Schacter (Eds.), *Neuropsychology of memory* (pp. 225-238). New York: Guilford.

Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J. et al. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioral Brain Research, 199*, 61-75.

Driskell, J., Copper, C., & Moran, A. (1994). Does mental practice enhance performance? *Journal of Applied Psychology, 79*, 481-492.

Engel, A. K., Maye, A., Kurthen, M., & König, P. (2013). Where's the action? The pragmatic turn in cognitive science. *Trends in Cognitive Sciences, 17*, 203-209.

Epstein, M. L. (1980). The relationship of mental imagery and mental rehearsal to performance of a motor task. *Journal of Sport Psychology, 2*, 211-220.

Ericsson, K. A. (2007). Deliberate practice and the modifiability of body and mind: Toward a science of structure and acquisition of expert and elite performance. *International Journal of Sport Psychology, 38*, 4-34.

Ericsson, K. A., & Smith, J. (1991). Prospects and limits of the empirical study of expertise: An introduction. In K.A. Ericsson (Ed.), *Toward a general theory of expertise: Prospects and limits* (pp. 1-38). Cambridge: Cambridge University Press.

Ericsson, K. A., & Towne, T. J. (2010). Expertise. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*, 404-416.

Essig, K., Janelle, C., Borgo, F., & Koester, D. (2014). Attention and neurocognition. In A. G. Papaioannou & D. Hackfort, *Routledge Companion to Sport and Exercise Psychology* (pp. 253-271). London: Routledge.

Farah, M. (1984). The neurological basis of mental imagery: A componential analysis. *Cognition, 18*, 245-272.

Feltz, D., & Landers, D. (1983). The effects of mental practice on motor skill learning and performance: A meta-analysis. *Journal of Sport Psychology, 5*, 25-57.

Feltz, D. L., Landers, D. M., & Becker, B. J. (1988). A revised meta-analysis of the mental practice literature on motor skill learning. In National Research Council (Ed.), *Enhancing human performance, Part III: Improving motor performance*. Washington, D.C.: National Academy Press.

Fery, Y. (2003). Differentiating visual and kinesthetic imagery in mental practice Canadian. *Journal of Experimental Psychology, 57*, 1-10.

Finke, R. A. (1979). The functional equivalence of mental images and errors of movement. *Cognitive Psychology, 11*, 235-264.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of Human Learning* (pp. 243-255). New York: Academic Press.

Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont: Brooks/Cole.

Foerster, R. M. (2011). *Eye movement, attention, and memory processes during sensorimotor learning and automatization* (doctoral dissertation). Bielefeld University, Bielefeld.

Frank, C., Land, W. M., & Schack, T. (2013). Mental representation and learning: The influence of practice on the development of mental representation structure in complex action. *Psychology of Sport and Exercise, 14*, 353-361.

Frank, C., Land, W. M., Popp, C., & Schack, T. (2014). Mental representation and mental practice: Experimental investigation on the functional links between motor memory and motor imagery. *PLoS ONE, 9*, e95175.

French, K. E., & McPherson, S. L. (1999). Adaptations in response selection processes used during sport competition with increasing age and expertise. *International Journal of Sport Psychology, 30*, 173-193.

French, K. E., & McPherson, S. L. (2004). Development of expertise in sport. In M. R. Weiss (Ed.), *Developmental sport and exercise psychology: A lifespan perspective* (pp. 403-423). Morgantown: Fitness Information Technology.

French, K. E., & Thomas, J. R. (1987). The relation of knowledge development to children's basketball performance. *Journal of Sport Psychology, 9*, 15-32.

Gabriele, T. E., Hall, C. R., & Lee, T. D. (1989). Cognition in motor learning: Imagery effects on contextual interference. *Human Movement Science, 8*, 227-245.

Gentile, A. M. (1972). A working model of skill acquisition with application to teaching. *Quest, 17*, 3-23.

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: Lawrence Erlbaum.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Glazier, P. S., Davids, K., & Bartlett, R. M. (2003). Dynamical systems theory: A relevant framework for performance-oriented sports biomechanics research. *Sportscience, 7*, 1-7.

Glover, S., & Dixon, P. (2013). Context and vision effects on real and imagined actions: Support from the common representation hypothesis of motor imagery. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 1352-1364.

Goginsky, A., & Collins, D. (1996). Research design and mental practice. *Journal of Sports Sciences, 14*, 381-392.

Goschke, T. (1996). Wille und Kognition: Zur funktionalen Architektur der intentionalen Handlungssteuerung. In H. Heckhausen & J. Kuhl (Hrsg.), *Motivation, Volition, Handlung* (S. 583-663). Göttingen: Hogrefe.

Goss, S., Hall, C., Buckolz, E., & Fishburne, G. (1986). Imagery ability and the acquisition and retention of movements. *Memory and Cognition, 14*, 469-477.

Göhner, U. (1992). *Einführung in die Bewegungslehre des Sports, Teil 1: Die sportlichen Bewegungen*. Schorndorf: Hofmann.

Göhner, U. (1999). *Einführung in die Bewegungslehre des Sports, Teil 2: Bewegungslehre des Sports*. Schorndorf: Hofmann.

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

Grouios, G. (1992). Mental practice: A review. *Journal of Sport Behavior, 15*, 42-59.

Guillot, A., & Collet, C. (2005). Contributions from neurophysiological and psychological methods to the study of motor imagery. *Brain Research Reviews, 50*, 387-397.

Guillot, A., & Collet, C. (2010). *The neurophysiological foundations of mental and motor imagery*. Oxford: Oxford University Press.

Guillot, A., Lebon, F., & Collet, C. (2010). Electromyographic activity during motor imagery. In A. Guillot & C. Collet (Eds.), *The neurophysiological foundations of mental and motor imagery* (pp. 83-94). Oxford: Oxford University Press.

Guillot, A., Di Rienzo, F., & Collet, C. (2014). The neurofunctional architecture of motor imagery. In T. D. Papageorgiou, G. I. Christopoulos, & S. M. Smirnakis (Eds.), *Advanced brain neuroimaging topics in health and disease: Methods and applications* (pp. 421-443). Rijeka: InTech.

Guillot, A., Di Rienzo, F., MacIntyre, T., Moran, A., & Collet, C. (2012). Imagining is not doing but involves specific motor commands: A review of experimental data related to motor inhibition. *Frontiers in Human Neuroscience, 6*, Article 247.

Hall, C., & Martin, K. (1997). Measuring movement imagery abilities: A revision of the Movement Imagery Questionnaire. *Journal of Mental Imagery, 21*, 143-154.

Hall, C., Buckolz, E., & Fishburne, G. (1992). Imagery and the acquisition of motor skills. *Canadian Journal of Sport Sciences, 17*, 19-27.

Halsband, U., & Lange, R. K. (2006). Motor learning in man: A review of functional and clinical studies. *Journal of Physiology - Paris, 99*, 414-424.

Hamster, R. (2008). *Golf - das kurze Spiel*. München: BLV.

Hancock, G. R., Butler, M. S., & Fischman, M. G. (1995). On the problem of two-dimensional error scores: measures and analyses of accuracy, bias, and consistency. *Journal of Motor Behavior, 27*, 241-250.

Handford, C., Davids, K., Bennett, S., & Button, C. (1997). Skill acquisition in sport: Some applications of an evolving practice ecology. *Journal of Sports Sciences, 15*, 621-640.

Hardwick, R. M., Rottschy, C., Miall, R. C., & Eickhoff, S. B. (2013). A quantitative meta-analysis and review of motor learning in the human brain. *NeuroImage, 67*, 283-297.

Hardy, L., Mullen, R., & Jones, G. (1996). Knowledge and conscious control of motor actions under stress. *British Journal of Psychology, 87*, 621-636.

Head, H. (1926). *Aphasia and kindred disorders of speech*. Cambridge, England: Cambridge University Press.

Healy, A. F., & Wohldmann, E. L. (2012). Specificity and transfer of learning. *Psychology of Learning and Motivation, 57*, 227-253.

Heinen, T. (2005). *Mentale Repräsentationen und Kinematik von Bewegungen: Ein interdisziplinärer Ansatz zur Analyse strukturfunktionaler Zusammenhänge der Bewegungsorganisation* (Dissertation). Deutsche Sporthochschule Köln.

Heinen, T., & Schack, T. (2004). Bewegungsgedächtnis und Bewegungsausführung: Optimierung von Rotationsbewegungen im Gerätturnen. In M. Roscher (Hrsg.), *Lehren und Lernen im Gerätturnen* (S. 85-95). Hamburg: Czwalina.

Heinen, T., & Schwaiger, J. (2002). Optimierung des Trainingsprozesses im Kunstturnen durch kognitive Verfahren. In B. Strauß, M. Tietjens, N. Hagemann, & A. Stachelhaus (Eds.), *Expertise im Sport: Lehren, lernen, leisten* (S. 67-68). Köln: bps.

Heinen, T., Schwaiger, J., & Schack, T. (2002). Optimising gymnastics training with cognitive methods. In M. Koskolou, N. Geladas, & V. Klissouras (Eds.), *Proceedings of 7th annual Congress of the European College of Sport Science from July, 24th to July, 28th in Athens, Greece* (p. 608).

Heinen, T., Vinken, P., & Fink, H. (2011). The effects of directing the learner's gaze on skill acquisition in gymnastics. *Athletic Insight, 3*, 165-181.

Heinen, T., Mandry, S., Vinken, P.M., & Nicolaus, M. (2013). Motor skill acquisition influences learners' visual perception in gymnastics. *Science of Gymnastics Journal, 5*, 19-28.

Herbart, J. F. (1825). *Psychologie als Wissenschaft*. Königsberg: Verfasser.

Heuer, H. (1985). Wie wirkt mentale Übung? *Psychologische Rundschau, 36*, 191-200.

Hill, L. A. (2007). *Mental representation mediation in expert golf putting* (doctoral dissertation). Florida State University, Tallahassee.

Hinshaw, K. (1991). The effects of mental practice on motor skill performance: Critical evaluation and meta-analysis. *Imagination, Cognition and Personality, 11*, 3-35.

Hodges, N. J., & Williams, A. M. (2012). *Skill acquisition in sport. Research, theory and practice*. London: Routledge.

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* (pp. 161-183). Hoboken: Wiley.

Hoffmann, J. (1986). *Die Welt der Begriffe*. Berlin: Verlag der Wissenschaften.

Hoffmann, J. (1990). Über die Integration von Wissen in die Verhaltenssteuerung. *Schweizerische Zeitschrift für Psychologie, 49*, 250-265.

Hoffmann, J. (1993). *Vorhersage und Erkenntnis*. Göttingen: Hogrefe.

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics, 6*, 65-70.

Holmes, P.S., & Collins, D. J. (2001). The PETTLEP approach to motor imagery: A functional equivalence model for sport psychologists. *Journal of Applied Sport Psychology, 13*, 60-83.

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*, 849-937.

Huber, J. (1997). Differences in problem representation and procedural knowledge between elite and nonelite springboard divers. *The Sport Psychologist,11*,142-159.

Ivry, R. (1994). Repräsentationen beim motorischen Lernen: Phänomene und Theorien. In H. Heuer & S. Keele (Hrsg.), *Psychomotorik* (S. 321-410). Göttingen: Hogrefe.

Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C. L., & Doyon, J. (2001). Potential role of mental practice using motor imagery in neurologic rehabilitation. *Archives of Physical Medicine and Rehabilitation, 82*, 1133-1141.

Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C. L., & Doyon, J. (2003). Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery. *Neuroimage, 20*, 1171-1180.

Jacobson, E. (1931). Electrical measurement of neuromuscular states during mental activities. V. Variation of specific muscles contracting during imagination. *American Journal of Physiology, 94*, 115-121.

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

Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., & Hatfield, B. D. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport and Exercise Psychology, 22*, 167-182.

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences, 17*, 187-245.

Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia, 33*, 1419-1432.

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

Jeannerod, M. (2001). Neural simulation of action: a unifying mechanism for motor cognition. *Neuroimage, 14*, S103-S109.

Jeannerod, M. (2004). Actions from within. *International Journal of Sport and Exercise Psychology, 2*, 376-402.

Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. Oxford: Oxford University Press.

Jeannerod, M., & Decety, J. (1995). Mental motor imagery: A window into the representational stages of action. *Current Opinion in Neurobiology, 5*, 727-732.

Jeannerod, M., & Frak, V. (1999). Mental imaging of motor activity in humans. *Current Opinion in Neurobiology, 9*, 735-739.

Johnson, P. (1980). The functional equivalence of imagery and movement. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 34*, 349-365.

Johnson, A. (2012). Procedural memory and skill acquisition. In I. B. Weiner, A. F. Healy, & R. W. Proctor (Eds.), *Handbook of psychology. Experimental psychology* (pp. 495-520). Hoboken: Wiley.

Kantak, S. S., & Winstein, C. J. (2012). Learning-performance distinction and memory processes for motor skills: A focused review and perspective. *Behavioral Brain Research, 228*, 219-231.

Keele, S.W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70*, 387-403.

Kelly, A. M., & Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cerebral Cortex, 15*, 1089-1102.

Kelso, S. (1981). On the oscillatory basis of movement. *Bulletin of the Psychonomic Society, 18*, 63.

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

Koch, I., Keller, P. E., & Prinz, W. (2004). The ideomotor approach to action control: Implications for skilled performance. *International Journal of Sport and Exercise Psychology, 2*, 362-375.

Kosslyn, S. M., Thompson, W. L., & Ganis, G. (2010). *The case for mental imagery*. Oxford: Oxford University Press.

Körndle, H. (1983a). *Zur kognitiven Steuerung des Bewegungslernens* (Dissertation). Universität Oldenburg.

Körndle, H. (1983b). Motorisches Lernen als kognitiver Prozess: Die Beziehung interner Repräsentation zur Ausführung von Bewegungen. In H. Rieder (Hrsg.), *Motorik- und Bewegungsforschung* (S. 178-182). Schorndorf: Hofmann.

Kromer, M. (2007). *Veränderungen von Gedächtnisrepräsentationen im motorischen Lernprozess: Theoretische Überlegungen und eine Pilotstudie zum Konzept impliziter Bewegungsrepräsentation* (Dissertation). Deutsche Sporthochschule Köln.

Kromer, M., & Schack, T. (2002). Entwicklung kognitiver Strukturen beim Erlernen des Einradfahrens. In B. Strauß, M. Tietjens, N. Hagemann, & A. Stachelhaus (Hrsg.), *Expertise im Sport: Lehren, lernen, leisten* (S. 213-214). Köln: bps.

Lacey, S., & Lawson, R. (2013). *Multisensory imagery*. New York: Springer.

Lafleur, M. F., Jackson, P. L., Malouin, F., Richards, C. L., Evans, A. C., & Doyon, J. (2002). Motor learning produces parallel dynamic functional changes during the execution and imagination of sequential foot movements. *Neuroimage, 16*, 142-157.

Land, W. M., Frank, C., & Schack, T. (2014). The impact of attentional focus on the development of skill representation in a complex action. *Psychology of Sport and Exercise, 15*, 30-38.

Land, W. M., Volchenkov, D., Bläsing, B., & Schack, T. (2013). From action representation to action execution: Exploring the links between cognitive and biomechanical levels of motor control. *Frontiers in Computational Neuroscience, 7*, Article 127.

Lander, H.-J. (1991). Ein methodischer Ansatz zur Ermittlung der Struktur und der Dimensionierung einer intern-repräsentierten Begriffsmenge. *Zeitschrift für Psychologie, 199*, 167-176.

Lander, H.-J. (1992). Eine differentialpsychologische Analyse begrifflich-strukturierten Wissens. *Zeitschrift für Psychologie, 200*, 181-197.

Lippens, V. (1992). *Die Innensicht beim motorischen Lernen. Untersuchungen zur Veränderung der Subjektiven Theorien bei Lern- und Optimierungsprozessen am Beispiel des Ruderns*. Köln: Strauß.

Lippens, V. (2001). Einsichten in sportmotorische Lern- und Optimierungsprozesse durch die (Re-) Konstruktion von Subjektiven Theorien. In J. Nitsch & H. Allmer (Hrsg.), *Denken Sprechen Bewegen* (S. 93-99). Köln: bps.

Lippens, V. (2009). Ist die 'Innensicht' out? Zur Rekonstruktion der Eigensichten beim Bewegen. *Leipziger Sportwissenschaftliche Beiträge, 50*, 13-33.

Lotze, M., & Halsband, U. (2006). Motor imagery. *Journal of Physiology – Paris, 99*, 386-395.

Lutz, R. S. (2003). Covert muscle excitation is outflow from the central generation of motor imagery. *Behavioral Brain Research, 140*, 149-163.

Mackay, D. (1981). The problem of rehearsal or mental practice. *Journal of Motor Behavior, 13*, 274-285.

Magill, R. A. (2011). *Motor learning and control: Concepts and applications*. New York: McGraw-Hill.

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport and Exercise Psychology, 29*, 457-478.

Masters, R. S. W. (1992). Knowledge, knerves and know-how: the role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology, 83*, 343-358.

McAvinue, L., & Robertson, I. (2009). Motor imagery: A multidimensional ability. *Journal of Mental Imagery, 33*, 99-120.

McBride, E. R., & Rothstein, A. L. (1979). Mental and physical practice and the learning and retention of open and closed skills. *Perceptual and Motor Skills, 49*, 359-365.

McCracken, H. D., & Stelmach, G. E. (1977). A test of the schema theory of discrete motor learning. *Journal of Motor Behavior, 9*, 193-201.

McPherson, S. L. (1993). Knowledge representation and decision-making in sport. In J. Starkes & F. Allard (Eds.), *Cognitive issues in motor expertise* (pp. 159-188). Amsterdam: Elsevier.

McPherson, S. L., & Kernodle, M. W. (2003). Tactics, the neglected attribute of expertise: PR and performance skills in tennis. In J. L. Starkes, & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise* (pp. 137-167). Champaign, IL: Human Kinetics.

McPherson, S. L., & Thomas, J. R. (1989). Relation of knowledge and performance in boys' tennis: age and expertise. *Journal of Experimental Child Psychology, 48*, 190-211.

McPherson, S. L., & Vickers, J. N. (2004). Cognitive control in motor expertise. *International Journal of Sport and Exercise Psychology, 2*, 274-300.

Mechsner, F. (2004). Perceptual-cognitive control of bimanual coordination. *International Journal of Sport and Exercise Psychology, 2*, 210-238.

Meijer, O., & Roth, K. (1991). *Complex movement behaviour: "The" motor-action controversy.* Amsterdam: North-Holland.

Meinel, K., & Schnabel, G. (1987). *Bewegungslehre, Sportmotorik*. Berlin: Volk und Wissen.

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

Mervis, C. B., & Rosch, E. (1981). Categorization of natural objects. *Annual Review of Psychology, 32*, 89-113.

Michaels, C. F., & Beek, P. J. (1995). The state of ecological psychology. *Ecological Psychology, 7*, 259-278.

Mitra, S., Amazeen, P. G., & Turvey, M. T. (1998). Intermediate motor learning as decreasing active (dynamical) degrees of freedom. *Human Movement Science, 17*, 17-66.

Moran, A., Guillot, A., MacIntyre, T., & Collet, C. (2012). Re-imagining motor imagery: Building bridges between cognitive neuroscience and sport psychology. *British Journal of Psychology, 103*, 224-247.

Morris, P., & Spittle, M. (2012). A default hypothesis of the development of internal and external imagery perspectives. *Journal of Mental Imagery, 36*, 1-30.

Morris, T., Spittle, M., & Watt, A. (2005). *Imagery in sport*. Champaign: Human Kinetics.

Mowbray, G. H., & Rhoades, M. V. (1959). On the reduction of choice reaction times with practice. *Quarterly Journal of Experimental Psychology, 11*, 16-23.

Mulder, T., de Vries, S., & Zijlstra, S. (2005). Observation, imagination and execution of an effortful movement: More evidence for a central explanation of motor imagery. *Experimental Brain Research, 163*, 344-351.

Mulder, T., Zijlstra, S., Zijlstra, W., & Hochstenbach, J. (2004). The role of motor imagery in learning a totally novel movement. *Experimental Brain Research, 154*, 211-217.

Munzert, J. (2001). Vorstellung und Bewegung. In J. R. Nitsch & H. Allmer (Hrsg.), *Denken Sprechen Bewegen* (S. 41-56). Köln: bps.

Munzert, J., & Zentgraf, K. (2009). Motor imagery and its implications for understanding the motor system. In M. Raab, J. Johnson, & H. Heekeren (Eds.), *Progress in Brain Research. Mind and motion: The bidirectional link between thought and action* (pp. 279-288). Amsterdam: Elsevier.

Munzert, J., Reiser, M., & Zentgraf, K. (2014). Bewegungsvorstellungstraining im Sport. In K. Zentgraf (Hrsg.), *Kognitives Training im Sport* (S. 9-36). Göttingen: Hogrefe.

Munzert, J., Zentgraf, K., Stark, R., & Vaitl, D. (2008). Neural activation in cognitive motor processes: Comparing motor imagery and observation of gymnastic movements. *Experimental Brain Research, 188*, 437-444.

Murphy, S. M. (1990). Models of imagery in sport psychology: A review. *Journal of Mental Imagery, 14*, 153-172.

Murphy, S., Nordin, S., & Cumming, J. (2008). Imagery in sport, exercise, and dance. In T. S. Horn (Ed.), *Advances in sport psychology* (pp. 297-324). Champaign Human Kinetics.

Narciss, S. (1993). *Empirische Untersuchungen zur kognitiven Repräsentation bewegungsstruktureller Merkmale. Ein wissenspsychologischer Ansatz zur theoretischen Fundierung des Mentalen Trainings* (Dissertation). Universität Heidelberg.

Narciss, S. (1996). Wissenspsychologische Untersuchung zur Modifikation der internen Bewegungsrepräsentation mit Hilfe mentaler Trainingsformen. In R. Daugs, K. Blischke, F. Marschall, & H. Müller (Hrsg.), *Kognition und Motorik* (S. 173-180). Hamburg: Czwalina.

Narciss, S. (2001). Mentales Training sensomotorischer Fertigkeiten. In K. J. Klauer (Hrsg.), *Handbuch Kognitives Training* (S. 323-348). Göttingen: Hogrefe.

Narciss, S., Reischle, K., & Eberspächer, H. (1994). Mentales Training. Quasi-experimentelle Studie zur Erfassung und Modifikation der kognitiven Repräsentation bewegungsstruktureller Merkmale des Schwimmens. In J. R. Nitsch, & R. Seiler (Hrsg.), *Psychologisches Training* (S. 210-218). Sankt Augustin: Academia.

Nattkemper, D., & Ziessler, M. (2004). Cognitive control of action: The role of action effects [Editorial]. *Psychological Research, 68*, 71-73.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341-360). Dordrecht: Martinus Nijhoff.

Newell, K. M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42*, 213-237.

Newell, K. M. (2003). Schema theory (1975): Retrospectives and prospective. *Research Quarterly for Exercise and Sport, 74*, 383-388.

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1-55). Hillsdale, NJ: Erlbaum.

Newell, K. M., & Shapiro, D. C. (1976). Variability of practice and transfer of training: Some evidence toward a schema view of motor learning. *Journal of Motor Behavior, 8*, 233-243.

Newell, K. M., Liu, Y.-T., & Mayer-Kress, G. (2001). Time scales in motor learning and development. *Psychological Review, 108*, 57-82.

Nitsch, J. R. (2004). Handlungstheoretische Grundlagen der Sportpsychologie. In H. Gabler, J. R. Nitsch, & R. Singer (Hrsg.), *Einführung in die Sportpsychologie. Teil 1: Grundthemen* (S. 43-164).

Nitsch, J. R. (2009). Ecological approaches to sport activity: a commentary from an action-theoretical point of view. *International Journal of Sport Psychology, 40*, 152-176.

Pacherie, E. (2012). Action. In K. Frankish & W. Ramsey (Eds.), *Cambridge Handbook of Cognitive Science* (pp. 92-111). Cambridge: Cambridge University Press.

Pascual-Leone, A., Dang, N., Cohen, L. G., Brasil-Neto, J. P., Cammarota, A., & Hallett, M. (1995). Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *Journal of Neurophysiology, 74*, 1037-1045.

Pelz, D., & Frank, J. A. (2000). *Dave Pelz's putting bible: The complete guide to mastering the green*. New York: Doubleday.

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

Pylyshyn, Z. (2003). Return of the mental image: Are there really pictures in the brain? *Trends in Cognitive Sciences, 7*, 113-118.

Raisbeck, L. D., Wyatt, W. R., & Shea, J. B. (2012). A two process memory-based account four mental and physical practice differences. *Journal of Motor Behavior, 44*, 115-124.

Rand, W. (1971). Objective criteria for the evaluation of clustering methods. *Journal of the American Statistical Association, 66*, 846-850.

Reiser, M., Büsch, D., & Munzert, J. (2011). Strength gains by imagination of muscle actions with different ratios of physical to mental training. *Frontiers in Psychology, 2*, Article 194.

Richardson, A. (1967a). Mental practice: A review and discussion, part I. *The Research Quarterly, 38*, 95-107.

Richardson, A. (1967b). Mental practice: A review and discussion, part II. *The Research Quarterly, 38*, 263-273.

Richardson, J. (2011). *Träum nur weiter: Wie ich versuchte, in nur einem Jahr Handicap 0 zu erreichen*. München: Riva.

Rosch, E. (1978). Principles of categorization. In E. Rosch, & B. B. Loyd (Eds.), *Cognition and categorization* (pp. 27-48). Hillsdale: Erlbaum.

Rosch, E., & Mervis, D. B. (1975). Family resemblances: studies in the internal structure of categories. *Cognitive Psychology, 7*, 573-605.

Rose, D. J., & Christina, R. W. (2006). *A multilevel approach to the study of motor control and learning*. San Francisco: Benjamin-Cummings.

Ryan, E. D., & Simons, J. (1981). Cognitive demand, imagery, and frequency of mental rehearsal as factors influencing acquisition of motor skills. *Journal of Sport Psychology, 3*, 35-45.

Ryan, E. D., & Simons, J. (1983). What is learned in mental practice of motor skills: A test of the cognitive-motor hypothesis. *Journal of Sport Psychology, 5*, 419-426.

Sackett, R. S. (1934). The influence of symbolic rehearsal upon the retention of a maze habit. *Journal of General Psychology, 10*, 376-398.

Santos, J. M., & Embrechts, M. (2009). On the use of the adjusted rand index as a metric for evaluating supervised classification. In C. Alippi, M. Polycarpou, C. Panayiotou, & G. Ellinas (Eds.), *Artificial neural networks e ICANN, lecture notes in computer science* (pp. 175-184). Berlin, Heidelberg: Springer.

Schack, T. (2002). *Zur kognitiven Architektur von Bewegungshandlungen – modelltheoretischer Zugang und experimentelle Untersuchungen* (Habilitation). Deutsche Sporthochschule Köln.

Schack, T. (2003). Kognition und Emotion. In H. Mechling & J. Munzert (Hrsg.), *Handbuch Bewegungswissenschaft Bewegungslehre* (S. 313-330). Schorndorf: Hofmann.

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

Schack, T. (2006). Mentales Training. In M. Tietjens & B. Strauss (Hrsg.), *Handbuch Sportpsychologie* (S. 254-261). Schorndorf: Hofmann.

Schack, T. (2010). *Die kognitive Architektur menschlicher Bewegungen: Innovative Zugänge für Psychologie, Sportwissenschaft und Robotik*. Aachen: Meyer & Meyer.

Schack, T. (2012). Measuring mental representations. In G. Tenenbaum, R. C. Eklund, & A. Kamata (Eds.), *Measurement in sport and exercise psychology* (pp. 203-214). Champaign: Human Kinetics.

Schack, T., & Bar-Eli, M. (2007). Psychological factors in technical preparation. In B. Blumenstein & R. Lidor (Eds.), *Psychology of sport training* (pp. 62-103). 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* (pp. 332-351). Hoboken: Wiley.

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

Schack, T., & Ritter, H. (2009). The cognitive nature of action: Functional links between cognitive psychology, movement science and robotics. In M. Raab, J. Johnson, & H. Heekeren (Eds.), *Progress in brain research. Mind and motion: The bidirectional link between thought and action* (pp. 231-252). Amsterdam: Elsevier.

Schack, T., & Ritter, H. (2013). Representation and learning in motor action: Bridges between experimental research and cognitive robotics. *New Ideas in Psychology, 31*, 258-269.

Schack, T., & Heinen, T. (2000). Mental training based on mental representation. In B. Carlsson, U. Johnson, & F. Wetterstrand (Eds.), Sport psychology conference in the new millenium: A dynamic research-practice perspective (pp. 333-337). Sweden: Halmstadt University.

Schack, T., Essig, K., Frank, C., & Koester, D. (2014). Mental representation and motor imagery training. *Frontiers in Human Neuroscience, 8*, 328.

Schack, T., Bertollo, M., Koester, D., Maycock, J., & Essig, K. (2014). Technological advancements in sport psychology. In A. G. Papaioannou & D. Hackfort, *Routledge Companion to Sport and Exercise Psychology* (pp. 953-966). London: Routledge.

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

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

Schmidt, R. A. (1985). The search for invariance in skilled movement behaviour. *Research Quarterly for Exercise and Sport, 65*, 188-200.

Schmidt, R. A. (2003). Motor schema theory after 27 years: Reflections and implications for a new theory. *Research Quarterly for Exercise and Sport, 74*, 366-375.

Schmidt, R. C., & Fitzpatrick, P. (1996). Dynamical perspective on motor learning. H. N. Zelaznik (Ed.), *Advances in motor learning and control* (pp. 195-223). Champaign: Human Kinetics.

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

Schmidt, R., A., & Lee, T. D. (2011). *Motor control and learning: A behavioral emphasis*. Champaign: Human Kinetics.

Schmidt, R., & Wrisberg, C. (2008). *Motor learning and performance. A situation-based learning approach*. Champaign: Human Kinetics.

Schuster, C., Hilfiker, R., Amft, O., Scheidhauer, A., Andrews, B., Butler, J. et al. (2011). Best practice for motor imagery: A systematic literature review on motor imagery training elements in five different disciplines. *BMC Medicine, 9*, 75.

Seidler, R. D., & Meehan, S. K. (2013). Introduction to the special topic: A multidisciplinary approach to motor learning and sensorimotor adaptation [Editorial]. *Frontiers in Human Neuroscience, 7*, Article 543.

Seiler, R. (1995). *Kognitive Organisation von Bewegungshandlungen. Empirische Untersuchungen mit dem Inversionsprinzip*. Sankt Augustin: Academia.

Seiler, R. (1997). Untersuchungen zu internen Bewegungsrepräsentation von Ruderern. In J. R. Nitsch, A. Neumaier, H. de Marées, & J. Mester (Hrsg.), *Techniktraining: Beiträge zu einem interdisziplinären Ansatz* (S. 459-486). Schorndorf: Hofmann.

Seiler, R. (2000). The intentional link between environment and action in the acquisition of skill. *International Journal of Sport Psychology, 31*, 496-514.

Shea, C., & Kohl, R. (1990). Specifity and variability of practice. *Research Quarterly for Exercise and Sport, 61*, 169-177.

Shea, C. H., & Wulf, G. (2005). Schema theory: A critical appraisal and reevaluation. *Journal of Motor Behavior, 37*, 85-102.

Sherwood, D. E., & Lee, T. D. (2003). Schema theory: Critical review and implications for the role of cognition in a new theory of motor learning. *Research Quarterly for Exercise and Sport, 74*, 376-382.

Shin, Y., Proctor, R., & Capaldi, E. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin, 136*, 943-974.

Smith, D., & Collins, D. (2004). Mental practice, motor performance, and the late CNV. *Journal of Sport and Exercise Psychology, 26*, 412-426.

Smith, D., Wright, C., & Cantwell, C. (2008). Beating the bunker: The effect of PETTLEP imagery on golf bunker shot performance. *Research Quarterly for Exercise and Sport, 79*, 385-391.

Smyth, M. M. (1975). The role of mental practice in skill acquisition. *Journal of Motor Behavior, 7*, 199-206.

Spittle, M., & Kremer, P. (2010). Mental practice and the retention of motor learning: A pilot study. *Perceptual and Motor Skills, 110*, 888-896.

Stebbins, R. J. A. (1968). A comparison of the effects of physical and mental practice in learning a motor skill. *Research Quarterly, 39*, 714-720.

Stöckel, T., Hughes, C. M. L., & Schack, T. (2012). Representation of grasp postures and anticipatory motor planning in children. *Psychological Research, 76*, 768-776.

Summers, J. (2004). A historical perspective on skill acquisition. In N. J. Hodges & Mark A. Williams (Eds.), *Skill acquisition in sport: Research, theory and practice* (pp. 1-26). London: Routledge.

Taktek, K. (2004). The effects of mental imagery on the acquisition of motor skills and performance: A literature review with theoretical implications. *Journal of Mental Imagery, 28*, 79-114.

Tenenbaum, G. (2003). Expert athletes: An integrated approach to decision making. In J. L. Starkes, & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise* (pp. 191-218). Champaign: Human Kinetics.

Tenenbaum, G., & Gershgoren, L. (2014). Individual and team decision-making. In A. G. Papaioannou & D. Hackfort, *Routledge Companion to Sport and Exercise Psychology* (pp. 460-479). London: Routledge.

Tulving, E., & Craik, F. I. M. (2000). *The Oxford Handbook of Memory*. Oxford: Oxford University Press.

Turvey, M. T. (1991). Action and perception from an ecological point of view. In R. Daugs (Ed.), *Sportmotorisches Lernen und Techniktraining. Internationales Symposium Motor Learning and Movement Behavior* (S. 78-95). Schorndorf: Hofmann.

Turvey, M. T., & Kugler, P. N. (1984). An ecological approach to perception and action. In H. T. A. Whiting (Ed.), *Human motor actions. Bernstein reassessed* (pp. 373-412). Amsterdam: Elsevier.

Ungerleider, L. G., Doyon, J., & Karni, A. (2002). Imaging brain plasticity during motor skill learning. *Neurobiology of Learning and Memory, 78*, 553-564.

Velentzas, K. (2010). *Mental representations, routines, and mental training in volleyball* (doctoral dissertation). German Sport University, Cologne.

Velentzas, K., Heinen, T., Tenenbaum, G., & Schack, T. (2010). Functional mental representation of volleyball routines in German youth female national players. *Journal of Applied Sport Psychology, 22*, 474-485.

Vickers, J. N (1992). Gaze control in putting. *Perception, 21*, 117-132.

Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 342-254.

Vickers, J. N. (2007). *Perception, cognition, and decision training: The quiet eye in action*. Champaign: Human Kinetics.

Vickers, J. N. (2009). Advances in coupling perception and action: The quiet eye as a bidirectional link between gaze, attention, and action. In M. Raab, J. G. Johnson, & H. R. Heekeren (Eds.), *Progress in Brain Research. Mind and motion: The bidirectional link between thought and action* (pp. 279-288). Amsterdam: Elsevier.

Vine, S. J., & Wilson, M. R. (2010). Quiet eye training: Effects on learning and performance under pressure. *Journal of Applied Sport Psychology, 22*, 361-376.

Wadden, K. P., Borich, M. R., & Boyd, L. A. (2012). Motor skill learning and its neurophysiology. In N. J. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport* (pp. 247-265). London: Routledge.

Walter, C., Lee, T. D., & Sternad, D. (1998). The dynamic systems approach to motor control and learning: Promises, potential limitations, and future directions [Editorial]. *Research Quarterly for Exercise and Sport, 69*, 316-318.

Wakefield, C., Smith, D., Moran, A. P., & Holmes, P. (2013). Functional equivalence or behavioural matching: A critical reflection on 15 years of research using the PETTLEP model of motor imagery. *International Review of Sport and Exercise Psychology, 6*, 105-121.

Weigelt, M., Schack, T., & Kunde, W. (2007). Attentional focus effects highlight the role of mental representations in motor control. *Bewegung und Training, 1*, 51-52.

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*, 231-235.

White, A., & Hardy, L. (1995). Use of different imagery perspectives on the learning and performance of different motor skills. *British Journal of Psychology, 86*, 169-180.

Wiemeyer, J. (1994a). *Interne Bewegungsrepräsentation. Grundlagen, Probleme und Perspektiven*. Köln: bps.

Wiemeyer, J. (1994b). Interne Bewegungsrepräsentationen. Grundlagen und Probleme eines komplexen Konstrukts. *Sportwissenschaft, 24*, 233-253.

Wiemeyer, J. (2001). Bewusste Bewegungsrepräsentation: Komponenten, Zusammenhänge und Lerndynamik. In J. R. Nitsch & H. Allmer (Hrsg.), *Denken Sprechen Bewegen* (S. 131-137). Köln: bps.

Williams, A. M., Davids, K., & Williams, J. G. P. (1999). *Visual perception and action in sport*. London: E. & F. N. Spon.

Williams, A. M., Singer, R. N., & Frehlich, S. G. (2002). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behavior, 34*, 197-207.

Williams, S. E., Cooley, S. J., Newell, E., Weibull, F., & Cumming, J. (2013). Seeing the difference: Developing effective imagery scripts for athletes. *Journal of Sport Psychology in Action, 4*, 109-121.

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review, 105*, 558-584.

Wilson, M. R., & Pearcy, R. C. (2009). Visuomotor control of straight and breaking golf putts. *Perceptual and Motor Skills, 109*, 555-562.

Wohldmann, E. L., Healy, A. F., & Bourne, L. E. (2007). Pushing the limits of imagination: Mental practice for learning sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*, 254-261.

Wohldmann, E., Healy, A., & Bourne, L. (2008). A mental practice superiority effect: less retroactive interference and more transfer than physical practice. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*, 823-833.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience, 12*, 739-51.

Wrisberg, C. A., & Ragsdale, M. R. (1979). Cognitive demand and practice level: Factors in the mental rehearsal of motor skills. *Journal of Human Movement Studies, 5*, 201-208.

Wulf, G., Horstmann, G., & Choi, B. (1995). Does mental practice work like physical practice without information feedback? *Research Quarterly for Exercise and Sport, 66*, 262-267.

Yue, G., & Cole, K. J. (1992). Strength increases from the motor program: Comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology, 67*, 1114-1123.

Zhang, H., Long, Z., Ge, R., Xu, L., Jin, Z., Yao, L., & Liu, Y. (2014). Motor imagery learning modulates functional connectivity of multiple brain systems in resting state. *PLoS ONE, 9*, e85489.

Zhang, H., Xu, L., Wang, S., Xie, B., Guo, J., Long, Z., & Yao, L. (2011). Behavioral improvements and brain functional alterations by motor imagery training. *Brain Research, 1407*, 38-46.

Zhang, H., Xu, L., Zhang, R., Hui, M., Long, Z., Zhao, X., & Yao., L. (2012). Parallel alterations of functional connectivity during execution and imagination after motor imagery learning. *PLoS ONE, 7*, e36052.

Zimmer, A. C., & Körndle, H. (1988). A model for hierarchically ordered schemata in the control of skilled motor action. *Gestalt Theory, 10*, 85-102.

FURTHER SCIENTIFIC CONTRIBUTIONS

Journal contributions

Land, W. M., Frank, C., & Schack, T. (2014). The impact of attentional focus on the development of skill representation in a complex action. *Psychology of Sport and Exercise, 15*, 30-38.

Schack, T., Essig, K., Frank, C., & Koester, D. (2014). Mental representation and motor imagery training. *Frontiers in Human Neuroscience, 8*, 328.

Conference contributions (Talks)

Simonsmeier, B., Frank, C., Schneider, M., & Gubelmann, H. (2014). Der Einfluss von Vorstellungstraining auf die Leistung und mentale Repräsentation des Rückschwungs in den Handstand bei 7-14 jährigen Turnerinnnen. *Dimensionen des Bewegungslernens im Turnen. Jahrestagung der dvs-Kommission Gerätturnen vom 01.-03.09.2014 in Hildesheim*.

Frank, C., Land, W. M., & Schack, T. (2014). Just do it?! The influence of physical and mental practice on performance, mental representation, and the quiet eye in golf putting. In R. Frank, I. Nixdorf, F. Ehrlenspiel, A. Geipel, A. Mornell, & J. Beckmann (Hrgs.), *Performing under pressure. Internationales und interdisziplinäres Symposium: 46. Jahrestagung der Arbeitsgemeinschaft für Sportpsychologie (asp) vom 29.-31.05.2014 in München* (S. 95). Hamburg: Feldhaus.

Frank, C., Land, W. M., & Schack, T. (2014). Perceptual-cognitive changes during skill acquisition: The influence of physical and mental practice on performance, mental representation structure, and the quiet eye in golf putting. *Annual meeting of the Research on Imagery and Observation (RIO) group from May, 15th to May, 16th 2014 in Brussels, Belgium*.

MacIntyre, T., Moran, A., Guillot, A., Collet, C., Di Rienzo, F., McAvinue, L., et al. (2014). New paradigms and new directions in motor cognition: Eye-tracking as a validation of self-reported imagery experience. *Annual meeting of the Research on Imagery and Observation (RIO) group from May, 15th to May, 16th 2014 in Brussels, Belgium.*

MacIntyre, T., Moran, A., Guillot, A., Collet, C., Di Rienzo, F., McAvinue, L., et al. (2014). New paradigms and new directions in motor cognition: The role of dual-task methods in elucidating multisensory imagery processes. *Annual meeting of the Research on Imagery and Observation (RIO) group from May, 15th to May, 16th 2014 in Brussels, Belgium.*

Frank, C., Essig, K., & Schack, T. (2013). Mental representation and mental practice: The influence of imagery rehearsal on representation structure, gaze behavior and performance. In T. Pfeiffer & K. Essig (Eds.), *Proceedings of the 1st International Workshop on Solutions for Automatic Gaze Data Analysis (SAGA) from October, 24th to October, 25th 2013 in Bielefeld, Germany* (pp. 6-9).

Vogel, L., Frank, C., & Schack, T. (2013). Mental representation and virtual reality agents. Harmony and Excellence in Sport and Life. *13th ISSP World Congress of Sport Psychology from July, 21st to July, 25th in Beijing, China.*

Frank, C., Land, W. M., & Schack, T. (2013). Behind the curtain: The influence of mental practice on the development of mental representation structure in early skill acquisition. *Annual meeting of the Research on Imagery and Observation (RIO) group from May, 09th to May, 10th 2013 in Dublin, Ireland.*

Frank, C., Vogel, L., & Schack, T. (2012). Mental imagery and mental representation – How to use biological data on technical platforms. In A. G. Di Nuovo, V.M. De La Cruz, & D. Marocco (Eds.), *Proceedings of the Workshop on Artificial Mental Imagery in Cognitive Systems and Robotics. 12th International Conference on Adaptive Behaviour (SAB) on August 27th 2012 in Odense, Denmark* (pp. 27-30).

Frank, C., Land, W. M. & Schack, T. (2012). Die Wirkung Mentalen Trainings auf die mentale Repräsentationsstruktur beim Fertigkeitserwerb. In M. Wegner, J.-P. Brückner, & S. Kratzenstein (Hrgs.), *Sportpsychologische Kompetenz und Verantwortung. 44. Jahrestagung der Arbeitsgemeinschaft für Sportpsychologie (asp) vom 17.-19.05.2012 in Kiel/ Oslo* (S. 71). Hamburg: Feldhaus.

Frank, C., Land, W. M., & Schack, T. (2012). Veränderung der Struktur mentaler Repräsentationen durch Übung. In H. Wagner, C. Bohn, & N. Eden (Hrsg.), *Neuromotion – Aufmerksamkeit, Automatisierung, Adaption. 9. gemeinsames Symposium der dvs- Sektionen Biomechanik, Sportmotorik und Trainingswissenschaft vom 21.-23.03.2012 in Münster* (S. 103). Münster: Uni-Print Münster.

Conference contributions (Poster)

de Kok, I., Hough, J., Frank, C., Schlangen, D., & Kopp, S. (2014). Dialogue structure of coaching sessions. *Proceedings of the 18th SemDial Workshop on the Semantics and Pragmatics of Dialogue (DialWatt) from September, 1st to September, 3rd 2014 in Edinburgh, Great Britain*.

Wenske, K., Frank, C., Velentzas, K., & Schack, T. (2014). Weitsprungtraining mit Köpfchen: Der Einfluss eines Vorstellungstrainings auf die mentale Repräsentation und praktische Ausführung. In R. Frank, I. Nixdorf, F. Ehrlenspiel, A. Geipel, A. Mornell, & J. Beckmann (Hrgs.), *Performing under pressure. Internationales und interdisziplinäres Symposium: 46. Jahrestagung der Arbeitsgemeinschaft für Sportpsychologie (asp) vom 29.-31.05.2014 in München* (S. 219). Hamburg: Feldhaus.

Frank, C., Land, W. M., & Schack, T. (2013). Behind the curtain: The influence of practice on the development of mental representation structure in early skill acquisition. *The Development of Expertise and Excellence in Applied Sport Psychology. Proceedings of the FEPSAC Conference (p. 20) from May, 18th to May, 19th 2013 in Paris, France.* [Poster award, 4th prize]

Frank, C., Land, W. M., & Schack, T. (2012). Veränderung der Struktur mentaler Repräsentationen beim Fertigkeitserwerb. In R. Riemann (Hrsg.), *48. Kongress der Deutschen Gesellschaft für Psychologie (DGPs) vom 23.-27.09.2012 in Bielefeld* (S. 16). Lengerich: Pabst Science Publishers.

Lex, H., Frank, C., Knoblauch, A., & Schack, T. (2011). Individualisierte kognitive Diagnostik im Golf. In K. Hottenrott, O. Stoll & R. Wollny (Hrsg.), *Kreativität, Innovation, Leistung. 20. Sportwissenschaftlicher Hochschultag (dvs) vom 21.-23.09.2011 in Halle-Wittenberg* (S. 300). Hamburg: Feldhaus.