Imaging Imagining Actions

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2008

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Umeå University Medical Dissertations
New series No. 1211
ISSN 0346-6612
ISBN 978-91-7264-658-2
Printed at Print & Media, Umeå Universitet

Abstract

Olsson, C.-J. (2008). Imaging imagining actions. **Doctoral dissertation from the Department of Integrative Medical Biology, section for Physiology, Umeå University, S-901 87 Umeå, Sweden.**
ISBN: 978-91-7264-658-2

Mental training has been studied extensively for the past century but we are still not completely sure how it affects brain and behavior. The aim of this doctoral thesis was to examine one aspect of mental training i.e. motor imagery. In Study I, active high jumpers were trained for 6 weeks using a motor imagery mental training program. We measured behavioral effects in motor parameters such as total height, false attempts, take off angle, and bar clearance. A significant improvement was found on the bar clearance component compared to a control group of high jumpers that did not participate in the mental training program. The results emphasize the importance of using appropriate outcome measures since mental training may affect distinct features of the movement rather than the entire movement. Study II used fMRI (functional Magnetic Resonance Imaging) to examine the neural correlates of imagery for active high jumpers, and also how imagery training affects brain activity. Active high jumpers were compared to a control group of high jumping novices and the results showed that high jumpers were able to activate motor regions, whereas controls used parts of the visual system to perform imagery of the high jump. Thus, we were able to show how important well established motor representations are in order to achieve a neural overlap between imagery and action. In study III we examined the effects after motor, mental and combined motor and mental training on a finger tapping task. Behaviorally, even though mental training improved performance, adding mental training to motor training did not improve the results beyond only using motor training. Imaging results showed that motor and mental training engaged different neural systems, with motor training associated with motor activity and mental training with visual activity. The combination of motor and mental training activated both motor and visual systems. Additionally combining motor and mental training resulted in transfer to an untrained motor sequence and neural data indicated that cerebellum mediated the transfer. The overall findings explain how mental training can be used to improve motor performance and motor parameters. Moreover, it also illustrates that the neural processes underlying such improvements may be distinct from motor training and that the brain may react differently during mental training depending on prior physical experience of the action.

Key words: mental training, motor training, fMRI, internal imagery, motor representation, brain system, practice, learning, transfer, active, novices, imaging, athletes

Acknowledgments

After years spent inside the office it feels great to finally be out….okay, sorry, I know, I shouldn't lie, I've probably spend more time than most people at the local coffee places, and I might have had long lunches a few days of the week….but considering the amount of work that has been done on these places I have never been worried about not reaching the goal line, I have been excited and I have been looking forward to cross it.

First and foremost I would like to thank my academic coach and friend Lars Nyberg. You have managed to challenge me for almost four years! Many will ask you, including me, how did you do it? I would also like to thank my co-supervisor and friend, Bert Jonsson. I'm sorry for removing your favorite MT-region in the last analysis, sorry for messing with your head using the Cronbach's alpha inappropriately, and sorry for making you climb up "ölbackarna" with only a tiny rope for safety. Together we have had a lot of fun, and I'm sure you have learned, I mean, I know that I have learned a lot from both of you!

I would also like to thank my family for your continuous support, I love you!

Thank you, Camilla for sharing your incredible knowledge about how to always make time for a latte, about men, and about so many other things. Stefan, for always turning and twisting on all my ideas. Erika, how would I have survived without our little competitions? Johan for finally understanding how important gym card and lunch down town is, I never gave up on you!

This thesis would not have been a thesis unless CIF (Centrum för Idrottsforskning) would have supported me financially these past years. Thank you, that was money well spent!

Also, all my colleagues both at "fysiologen" and at "psykologen", thank you for creating a fun and stimulating workplace. Also, a big thank you to Anne and Ann-Kathrine for all the help during brain data collection. And of course, many thanks to all of my friends!

And last, but not least, my big and true love, sorry for these past few months when I've been spending more times analyzing, writing, and reading, and not with you, I am thankful that you make me leave the office, you do make me sore, but it is totally worth it…to hurdling and true challenges in life.

Umeå, October 2008
CJ Olsson

List of publications

This Doctoral Thesis is based on the following three papers. They will be referred to by their roman numerals.

I. Olsson, C.-J., Jonsson, B., & Nyberg, L. (2008). Internal imagery training in active high jumpers. *Scandinavian Journal of Psychology, 49(2)*, 133-140

II. Olsson, C.-J., Jonsson, B., Larsson, A., & Nyberg, L. (2008). Motor representations and practice affect brain systems underlying imagery: An fMRI study of internal imagery in novices and active high jumpers. *The Open Neuroimaging Journal*, 2, 5-13.

III. Olsson, C.-J., Jonsson, B., & Nyberg, L. (2008). Learning by doing and learning by thinking: An fMRI study of combining motor and mental training. *Frontiers in Human Neuroscience, 2(5)*.

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Contents

INTRODUCTION

Do you also catch yourself thinking about complex athletic actions, trying to understand how they are performed, wondering if you can perform them yourself, or is that just me? Nevertheless, I am sure that you have experienced a situation in which you mentally form images of a goal or of a dream. When we do this it is often to prepare ourselves for an event that we are about to experience. It is as if we are trying to experience the situation before we actually do it. Later, when the time has come for the event to take place, one can always wonder, was the mental training of any use, or did it not make any difference?

Historically, mental training has been appreciated since the early days of scientific research. William James (1890) suggested that mental training[1] probably differ, compared to motor training, by intensity rather than locality. That is, already at this early stage of investigating the underlying processes of mental training the idea of using similar neural regions as during motor execution was started. In the 1930s there was one line of research referring mental training to "something more" (Sackett, 1934). The meaning of that expression was that mental training gives us something more than just the coordinated pattern of a movement. Mental training gives us a representation of a symbolic character, which could turn out to be effective in a situation were that is important, in e.g. maze learning. Moreover, it was suggested that mental training would short-circuit the trial and error process we sometimes engage in, and, therefore, it was suggested that mental training was better for symbolic tasks rather than pure motor tasks (Perry, 1939). At about the same time, another line of research also grew stronger with Edmund Jacobson as a pioneer. He and others conducted experiments where participants were asked to mentally contract muscles of their arm with electrodes inserted into the muscles. The imagined contractions evoked a response from those muscles that were supposedly imagined to contract, and it was therefore suggested that mental training did not only affect closed circuits of the brain, but also affected more distal muscles (Jacobson, 1927, 1930, 1932). In the 1950s, 60s and 70s the number of studies exploring how mental training would affect actual sports performance increased. One study, for example, examined how mental training affects volleyball skills (Shick, 1970). It showed that

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[1] William James did not use the term mental training *per se*; he rather used the term motor imagery. During the first half of the 20th century there was no definition of mental training. However, as you will see, these two terms, mental training and motor imagery, are closely related.

three min of mental practice was more efficient than one min, and that mental training affected the serve skill rather than the volleying skill. Even though mental training is effective on sports skills we are still not entirely clear about the underlying mechanisms.

The aim of this thesis was to further explore mental training. First I will give an overview of mental training as a research subject including the underlying assumptions. I will then turn to motor training which, by reasons you will understand later, has influenced our knowledge about mental training. This will then be followed by a review of the research that has been done about the effects of mental training and how mental training should be used. I will then present three empirical studies that are the foundation of this thesis, and finally follow up with a general discussion about what these studies have brought to the knowledge about mental training and its effects on brain and behavior.

MENTAL TRAINING

The most widely used definition of mental training is that you mentally rehearse a task without any gross muscular movements (Richardson, 1967). Mental training is also often referred to as motor imagery. However, mental training has also been distinguished from motor imagery by Suinn (1985) who suggested that imagery involves the individual actually using imagery to improve motor skills. In mental training, on the other hand, individuals do not need to use imagery *per se*, the practice may be covert but could involve e.g. verbal rehearsal instead of imagery rehearsal. Also, the term mental training is often used when athletes are dealing with other mental aspects that could affect behavior during training and competition, such as arousal regulation, anxiety, and attention focus (Jones & Stuth, 1997). In my thesis, though, mental training is always equal with motor imagery and the only behavioral effect I aim to discuss is the change of motor behavior.

As the definition implies, having no gross movements does not mean that one necessarily should avoid all kinds of motion during mental training. Theoretically this has also been supported, and a model outlined to maximize the effects of mental training stated that despite that practitioners often instruct athletes to lie or sit comfortably, it is better to make mental training as close to motor preparation and execution as possible (Holmes & Collins, 2001). This has also been supported empirically with e.g. a study involving field hockey players (Smith, Wright, Allsopp, & Westhead, 2007). In this study one group was trained using imagery close to the actual sport by making the players imagine with the field hockey equipment and in the same environment as they were playing. This was compared to a control group that received traditional imagery instructions. The group that performed imagery closest to the actual sport showed greater improvements. Moreover, when basketball players were imagining free-throw shooting with or without holding the basketball, the time making the throw was more similar between imagery and execution for those players who held the ball compared to those who did not (Holmes & Collins, 2001). Hence, incorporating mental training with physical training, by using the same equipment and being at the same place as during task performance, seems to be more efficient than performing imagery in a relaxed position as often is suggested. Even though the Holmes & Collins model, as well as previous research, explains how important the similarities between mental training and motor training are, it fails to explain any specific requirements, in terms of experience or motor representations, that are necessary for individuals in order to make motor and mental training functionally similar.

Building blocks of mental training

Motor imagery

Imagery is the process in which an individual recalls or creates sensory experiences in the absence of external stimuli usually associated with these experiences (Murphy, 1994). A motor image is not a static image in any ways, it involves dynamic changes in the content of the image over a timescale, much similar to the actual execution of the action (Jeannerod, 2006). By imagining a motor action you activate a motor program, but you are inhibiting the outflow signals at a certain stage. Thus, motor imagery is the imagination of the performance of an action without actually intending to perform it (Jeannerod, 2001).

The definition of motor imagery by Jeannerod (1997) is that *motor imagery* is a force-generated representation of the self in action from a first person (internal) perspective. During imagery performance you access the hidden parts of the action, and also the processes leading to execution, but without performing the intended action (Jeannerod, 2006). One problem with motor imagery is that there is no clear reference to which the image can be compared. During imagery of an action you engage in a private event that is all in your mind. As a consequence, the process of motor imagery is difficult to share and explain. Take a visual image in contrast; a visual image is easily shared, you simply show a scene, an object or you verbalize it. Now take a complex action, such as turning with your bike. It is not easy to describe the precise coordination how to do that, even though most of us are able to execute it with only minor difficulties. Thus, motor images are difficult to transfer into verbal code, and therefore it makes them difficult to be shared, described, and studied (Jeannerod, 1995). Nevertheless, most of us would be able to imagine riding and turning with the bike, and, therefore, we could still use motor imagery to mentally rehearse the action.

All actions involve a covert stage which is a representation of the future. Thus, by studying motor imagery we are able to extend our understanding of not only the action but also the ongoing processes that precedes the action, and, thus, better understand actions and how action representations are created. It has been postulated that covert actions, such as motor imagery, indeed are actions but only for the fact that they are not being executed (Jeannerod, 2001). Further, it was also suggested that due to the presence of activation in the motor system during motor simulation, the action representation is in a true motor format. Thus, motor imagery should be regarded as a real action because it includes the goal of the action, how to reach it, and how it will affect the individual and the external world.

Motor representations

Each voluntary movement has an abstract representation, and prior to the execution the brain has formed a representation of the movement. The formation is not only a part of the movement; it is believed to comprise the entire movement, including the plan for execution as well as the intended results, and this formation is called the *motor representation* (Kandel, Schwartz, & Jessell, 2000). Since an action representation is believed to precede the execution of the same action it was suggested that it could be detached from the execution and exist on its own (Jeannerod, 2006). The process of motor representation is usually a non-conscious process, however, under certain conditions, such as mental training, it may be accessed consciously. Thus, motor imagery is a way to access the motor representation consciously (Jeannerod, 1994, 1995).

What is known about motor representations is predominantly established from studies investigating physical training. Therefore I now turn to motor training in order to see how researchers have been able to explain how the brain handles motor representations.

PHYSICAL TRAINING AND THE BRAIN

There is little doubt about motor learning being a central important aspect of our daily lives. Without remembering and creating new actions and action representations it would be an interesting challenge to drive to work each day, and I'm guessing, since the alternative would be to use Velcro, that no-one would enjoy having to re-learn how to tie the shoelaces every morning. Motor skill learning is referred to as the acquisition of a novel skill, or by putting different motor patterns together and forming a complex movement sequence such as a high jump or a baseball throw (Sanes, 2003). If the movement should be considered as complex or as simple depends on the experience of the learner (Luft & Buitrago, 2005). A skill is defined as a behavior acquired through practice, and should be distinguished from an ability which would be a trait that genetically characterizes an individual (Schmidt & Lee, 1999). Research has acknowledged the influence of genetic traits in sports performance, however, empirically only limited amount of research supports that exceptional performance, such as athletic performance, is driven by an innate talent (Starkes & Ericsson, 2003). Rather it is suggested that exceptional performance is influenced by experience and practice and only minimally by genetically defined traits (Ericsson, Krampe, & Tesch-Römer, 1993).

It has been suggested that motor skill learning is an outgrowth from motor control. If motor skill learning refers to increased spatial and temporal accuracy as a result of practice, then motor control refers to the actual planning and execution of the movement (Willingham, 1998). Thus, during motor learning motor control becomes tuned into a particular task and, therefore, operates more efficiently. When skills are acquired, the learner provides a voluntary effort to learn and, accordingly, learning procedures have been viewed as one of the key elements of voluntary behavior (Hikosaka et al., 1999). Moreover, it has been suggested that there is a functional hierarchy for human motor control in which any one behavior involves at least two levels of feedback control (Todorov, 2004). First a leading level monitors the progress and exploits the different paths one may have to achieve the goal. Second, a background level corrects the movements without which the leading level could not function. Growing evidence also supports that motor skills are learned through stages (Halsband & Lange, 2006). First there is the initial stage, during which it is critical to establish sensory cues with correct motor commands. After the initial stage, there is the intermediate stage, which is a gradual learning of the sensory-motor map, resulting in that sensory cues can be transformed fast and accurately into correct motor outputs. The last stage is the advanced stage, in which the movements have become automatic and can be performed fast and accurately. The staged learning process has shown to be true for visually guided motor skills (Hubert et al., 2007; Luft & Buitrago, 2005), and recently it was also shown for audio-guided skills (Säfström & Edin, 2006).

There are also distinct neural processes that underlie motor skill learning. Even at the neural level it has been supported that learning occurs through stages with different physiological processes appearing at each different phase (Karni et al., 1998; Kleim et al., 2004) in order for the learned skill to be stored as a procedural memory (Cohen & Squire, 1980). During the fast, initial phase, long-term potentiation (LTP) mechanisms at existing synapses are used to improve performance (Rioult-Pedotti, Friedman, Hess, & Donoghue, 1998; Rosenkranz, Kacar, & Rothwell, 2007). In later phases of motor skill learning motor-map reorganization occur (Karni et al., 1995; Kleim et al., 2004) with increased synaptic connectivity (Rosenkranz et al., 2007) and expansions of the motor representations (Hlustik, Solodkin, Noll, & Small, 2004).

Motor regions of the human brain

Through the different stages of motor skill learning different regions of the brain are involved. During the initial learning, activation in prefrontal regions is often reported, which has been considered to reflect decision and selection of movements (Deiber et al., 1997; Jueptner, Ottinger et al., 1997). In particular the dorsolateral pre-frontal cortex (DLPFC) has been suggested to be important in the early stages, likely due to its role in learning to associate visual cues and motor commands according to arbitrary rules (Halsband & Lange, 2006; Toni & Passingham, 1999). Therefore, the prefrontal cortex is active within the first hour after learning is finished, possibly acting as a temporary storage site for arbitrary sensorimotor associations (Shadmehr & Holcomb, 1997).

The pre-motor cortex consists of several different motor regions. The dorsal and ventral pre-motor areas are located on the surface of the hemispheres, whereas the supplementary motor area (SMA) is located on the medial wall of the hemispheres. The pre-motor cortex is thought to have necessary anatomical substrates to influence motor processing both at the cortical level and at the spinal level (Dum & Strick, 2002).

Early research suggested that the *SMA* was classified as a single cortical region within the medial part of Brodamann's area 6 (Penfield & Welch, 1951). However, more recent studies have shown that there are functional differences within the SMA (Chung, Han, Jeong, & Jack, 2005). Currently it is therefore agreed upon that the SMA should be divided into two distinct areas; the SMA proper and the more rostrally located pre-SMA (Picard & Strick, 1996, 2001; Tanji, 1996; Tanji & Shima, 1994). The pre-SMA is thought to be involved in the early stages of motor learning (Halsband & Lange, 2006; Hikosaka et al., 1996). Especially during sequential learning, (Kennerley, Sakai, & Rushworth, 2004; Sakai et al., 1999; Sakai et al., 1998), updating of movement plans (Kennerley et al., 2004; Matsuzaka & Tanji, 1996), and in relation to high task complexity (Meister et al., 2005). With practice and once a sequence is learned, activation in the pre-SMA is reduced (Nakamura, Sakai, & Hikosaka, 1998), and activity in SMA proper increases (Grafton, Woods, & Tyszka, 1993; Meister et al., 2005). In general, activation in SMA proper is more involved in aspects of motor control rather than learning (Picard & Strick, 2003; Russo, Backus, Ye, & Crutcher, 2002; Tanji, 2001), and also in tasks that require timing of movements (Van Mier, Tempel, Perlmutter, Raichle, & Petersen, 1998). However, jointly the pre-SMA and the SMA proper cooperate to produce sequential movements correctly (Hikosaka, Nakamura, Sakai, & Nakahara, 2002; Tanji, 2001; Willingham, 1998).

The *dorsal pre-motor area* (PMd) seems to play a key role when organizing movements (Meister et al., 2005), and in various aspects of movement generation and control (Picard & Strick, 2001). It is also suggested that the PMd is a site where sensorimotor integration occurs (Kurata, Tsuji, Naraki, Seino, & Abe, 2000), and is therefore active during both learning as well as during motor performance (Deiber et al., 1997; Grafton, Fagg, & Arbib, 1998; Grezes & Decety, 2001). There are also findings that support the PMd as a storage site for complex movements such as sports skills (Meister et al., 2005; Sakai, Ramnani, & Passingham, 2002).

The *ventral pre-motor area* (PMv) has also been found to be activated during motor execution (Grezes & Decety, 2001). However, Rizzolatti and colleagues (1998) suggested that within this region there are neurons with *mirror* properties, these are supposedly involved in action imitation and action recognition. Moreover, the PMv is involved in planning and selection of movements (Krams, Rushworth, Deiber, Frackowiak, & Passingham, 1998), especially for upper-limb movements (Grezes & Decety, 2001; Stephan et al., 1995). Studies have even shown that there are separate arm and hand areas within the PMv (Dum & Strick, 2002). Further, it has been proposed that another function of the PMv is to associate particular sensory cues with the correct response (Asaad, Rainer, & Miller, 1998; Petrides, 1997) and therefore PMv has a similar role as the PMd during learning of arbitrary visuo-motor associations (Toni & Passingham, 1999).

The *primary motor cortex* (M1) appears to have a role in the early consolidation phase of practice-related motor skill learning (Muellbacher et al., 2002; Sanes, 2003), and during training there is a functional reorganization within M1 (Hikosaka et al., 2002; Karni et al., 1995; Rioult-Pedotti, Friedman, & Donoghue, 2000). M1 projects to the spinal cord for motor control (Willingham, 1998). However by showing that the direction of a movement is expressed prior to the actual movement Georgopoulos (1986) were able to suggest that the M1 codes movements in terms of space and not in terms of muscle commands. Traditionally the M1 has been viewed as *the final common pathway* for the central control of movement. Yet, by reviewing the motor areas in the frontal lobe of the primate, Dum and Strick (2002) showed that the output of several pre-motor areas also terminated in the spinal cord in similar manners as the M1. Therefore it was suggested that pre-motor regions along with the M1 are used to generate and control movements.

Several studies support the role of *cerebellum* in motor learning. However, Seidler and colleagues (2002) showed that there were no activity in the cerebellum during encoding, i.e. learning, of a motor task. Although, during expression after learning was finished, there was activity found in the cerebellum. Still, Hubert and colleagues (2007) showed activation in the cerebellum both in early and late phases of motor learning. Therefore, they proposed different aspects of cerebellar activation during the different stages of learning, with a function of error detection and correction of inappropriate moves associated with the early phase, and the late phase for regulating movements. Other studies have also suggested that the cerebellum may be a possible storage site for long-term memories of motor skills (Hikosaka et al., 2002; Imamizu et al., 2000).

There are also *sub-cortical regions,* such as the basal ganglia, involved in motor learning. In the early phases of skill acquisition, activity in the basal ganglia is believed to reflect a strengthening of the sensorimotor associations made in the prefrontal cortex (Grafton, Hazeltine, & Ivry, 1995; Jueptner, Frith, Brooks, Frackowiak, & Passingham, 1997; Toni & Passingham, 1999). During the later phases of motor learning the basal ganglia are likely to have a role in the storage of learned sequences (Halsband & Lange, 2006). Also, Monchi and colleagues (Monchi, Petrides, Strafella, Worsley, & Doyon, 2006) suggested a role for the basal ganglia in planning and executing actions, and Doyon and Benali (2005) proposed that reorganization occurs within the basal ganglia from the associative to the sensorimotor territories of the striatum as a result of motor training. This suggestion was also recently underpinned by a study showing how hippocampus and striatum interact during motor sequence consolidation (Albouy et al., 2008).

In order for motor regions to cooperate and produce voluntary movements they engage in an intrinsic form of networking. Within the basal ganglia functional integration occurs in order to execute movements (Alexander & Crutcher, 1990). That is, the basal ganglia has connections to the SMA, pre-motor cortex, primary motor cortex and the frontal lobe, and thereby supports the executing of movements, as well as the preparation of movements. When a complex action is performed it is either internally or externally guided. An internally guided action would for example be a high jump, since the athlete starts the action on his or her own. This would be in contradiction to an externally guided action, which would be when a tennis player has to adjust the movements based on the opponent's position. The different requirements for different actions make different types of integration to occur in order to produce the intended actions. Goldberg (1985) suggested that there are two different loops, an internal and an external, that are responsible for the integration of information to produce the correct movement. The internal loop, the basal ganglia dependent loop, includes besides the basal ganglia also prefrontal cortex and the SMA. The basal ganglia gathers input from wide regions of the cortex, the information is integrated and sent back to a restricted pre-motor region. For actions that are externally guided a different loop, primarily using cerebellum and motor cortex, functions to use the context in order to refine the execution in later stages of motor behavior.

Access to motor representations using mental training

Jeannerod's theory, as previously described, predicts that there should be a neural overlap between imagining actions and executing actions and that this may be a reason for facilitation of motor performance following mental training (Jeannerod, 2001). In fact, several studies support neural similarities between action and imagery, at least to some extent.

During the past years a plethora of studies consistently show that during imagery of movements the SMA is activated (Dechent, Merboldt, & Frahm, 2004; Ehrsson, Geyer, & Naito, 2003; Gerardin et al., 2000; Hanakawa et al., 2003; Kim, Jennings, Strupp, Andersen, & Ugurbil, 1995; Kuhtz-Buschbeck et al., 2003; Lotze et al., 1999; Michelon, Vettel, & Zacks, 2006; Munzert, Zentgraf, Stark, & Vaitl, 2008; Olsson, Jonsson, Larsson, & Nyberg, 2008; Oullier, Jantzen, Steinberg, & Kelso, 2005; Owen et al., 2006; Roland, Larsen, Lassen, & Skinhoj, 1980; Solodkin, Hlustik, Chen, & Small, 2004; Stephan et al., 1995). Moreover, activation in the pre-motor cortex has been one of the most conspicuous findings during motor imagery, and especially the dorsal parts (Bakker et al., 2008; de Lange, Roelofs, & Toni, 2008; Gerardin et al., 2000; Kuhtz-Buschbeck et al., 2003; Stephan et al., 1995). Activation in the ventral parts has also been found during imagery (Binkofski et al., 2000; Gerardin et al., 2000; Kuhtz-Buschbeck et al., 2003), but also during movement observation and in action recognition in both humans (Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Hari et al., 1998), and in non-human primates (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996; Rizzolatti, Fogassi, & Gallese, 2001; Rizzolatti et al., 1998). The cerebellum is another motor region that often is activated when imagining movements (Gerardin et al., 2000; Lacourse, Turner, Randolph-Orr, Schandler, & Cohen, 2004; Luft, Skalej, Stefanou, Klose, & Voigt, 1998; Munzert et al., 2008; Naito et al., 2002).

Regarding the primary motor cortex several authors have reported activity during motor imagery (Caldara et al., 2004; Lotze et al., 1999; Munzert et al., 2008; Nair, Purcott, Fuchs, Steinberg, & Kelso, 2003; Pfurtscheller, Brunner, Schlogl, & da Silva, 2006; Schnitzler, Salenius, Salmelin, Jousmaki, & Hari, 1997; Sharma, Jones, Carpenter, & Baron, 2008). Moreover, studies of patients with lesions in the primary motor cortex have shown behavioral disturbances when tested on motor imagery tasks (Sirigu et al., 1995; Sirigu et al., 1996; Tomasino, Budai, Mondani, Skrap, & Rumiati, 2005). However, it is still unclear whether one should expect M1 activation during mental training or not because some studies have only showed it for a few participants (Gerardin et al., 2000; Leonardo et al., 1995; Porro et al., 1996) and some studies have shown that the M1 activity could be related to the actual motor response given at the end of an imagery task rather than the imagined task itself (de Lange, Hagoort, & Toni, 2005; Richter et al., 2000). Therefore, no consensus about M1 activation during mental training has been reached (see also, Parsons & Fox, 1998; Porro, Cettolo, Francescato, & Baraldi, 2000). It has been suggested that factors such as paradigm choice, the use of complex vs. simple tasks, and subject instructions also contributes to the different findings (Lotze & Halsband, 2006).

Functional equivalence between mental training and action

Considering that the activated brain regions during action generation and action simulation are related it has been suggested that there is a *functional equivalence* between mental training and motor performance (Grezes & Decety, 2001). In fact, some authors have suggested that motor imagery relies on the generation of a complete motor plan however it is prevented from operating on the body (Grush, 2004; Jeannerod, 1994). Whereas other authors, even though they do not argue against a functional equivalence, they tend to suggest that motor imagery more relies on the processes involved in planning of actions but not in the processes involved in the control of the movements (Glover, 2004; Johnson, Sprehn, & Saykin, 2002; Yue & Cole, 1992). Nevertheless the term functional equivalence is vital for mental training to be successfully used (Holmes & Collins, 2001), and it is not only within the brain similarities between mental training and motor execution are found. It has also been shown that there are similarities in terms of other physiological responses, i.e. during motor imagery similar physiological responses as during motor action are shown such as increased heart rate, CO_2-pressure and respiration frequency (Calabrese, Messonnier, Bijaoui, Eberhard, & Benchetrit, 2004; Decety, Jeannerod, Durozard, & Baverel, 1993; Decety, Jeannerod, Germain, & Pastene, 1991; Hale, 1982; Perry & Morris, 1995; Wuyam et al., 1995).

Studies also support that motor imagery and motor action are constrained by the same physical laws. This has been suggested by showing that the time it takes to physically execute an action is similar to the time it takes to mentally perform the same action (Decety & Jeannerod, 1996; Sirigu et al., 1995; Sirigu et al., 1996). Thus, the functional equivalence implies that imagery of an action is similar to physically performing the same action.

However, when breaking up a gymnastics routine in different parts (run phase, first and second flight phase) it was shown that even though the total time of the routine was not significantly different between performance and imagery, the different phases of the routine significantly differed between performance and imagery (Calmels, Holmes, Lopez, & Naman, 2006). The running phase was faster during imagery, and the two flight phases were faster during actual movement. Other studies have also showed that the time it takes for physical action not always equals the time of imagining the action (Reed, 2002). Moreover, it has generally been suggested that the time similarities between imagery and action are stronger for well known tasks compared to novel tasks (Guillot & Collet, 2005). Thus, not all studies are in favor of a functional equivalence between imagery and action.

PRACTICAL ISSUES WITH MENTAL TRAINING

Mental training perspectives

Jeannerod defined motor imagery as a first person perspective in which you feel as if you are executing the action without actually performing it (e.g., Jeannerod, 2006). However, Mahoney and Avener (1977) acknowledged that there are two perspectives one can use when engaging in motor imagery. Besides using the internal, first person, perspective there is also an external, third person, perspective, which would be used as if you watch yourself on TV. The imagery perspective used during mental training may affect the functional equivalence between imagery and performance, and, therefore, also have effects on the motor skill (Morris, Spittle, & Watt, 2005). Hence, research has been interested in possible differences the two perspectives may have on motor performance.

It has been shown that the internal perspective produces more EMG activity compared to the external perspective (Harris & Robinson, 1986) and also more physiological responses (Hale, 1982; Perry & Morris, 1995). Therefore one could argue that the internal perspective should be more effective than the external perspective (Holmes & Collins, 2001). Some have argued that it is a myth that internal imagery should be more effective than external imagery because the two perspectives are effective in different aspects of a performance, and, therefore, also should be used differently (Hall, 1997; Hardy, 1997). This is in line with others that have argued for the internal perspective to be more effective for details and technical characteristics of motor learning (Fery & Morizot, 2000; Holmes & Collins, 2001), whereas the external perspective may be more important for the temporal structure rather than for details (Smyth & Waller, 1998) and in observational learning (White & Hardy, 1995). It has also been suggested that the external perspective may add something new and different to the imagery experience such as motivational factors and competitive drive (Hardy, 1997; Morris et al., 2005; Spittle & Morris, 2007).

I have previously described that the motor representation contains the entire movement. Therefore having a well developed motor representation increases the *functional equivalence* between actual action and imagery (Jeannerod, 1995). It is also likely that the *motor representation* affects the perspective individuals' use. Consequently, in order to use the first person perspective, and increase the functional equivalence between imagery and action, a well developed motor representation would be beneficial. This is supported from imaging-studies showing that executed actions and imagined actions are more similar in skilled compared to novel performance (Lacourse, Orr, Cramer, & Cohen, 2005). Thus, in order to improve motor performance in experienced athletes, the internal perspective should be more effective (Hardy & Callow, 1999).

When to use mental training

Several studies support that most athletes in one way or the other engage in mental training to enhance their performance (Hall, Mack, Paivio, & Hausenblas, 1998; Hausenblas, Hall, Rodgers, & Munroe, 1999; Weinberg, Butt, Knight, Burke, & Jackson, 2003). When asking athletes why and when they use mental training they tend to answer that it is more in conjunction with competition rather than for learning purposes (Arvinen-Barrow, Weigand, Hemmings, & Walley, 2008; Munroe, Giacobbi, Hall, & Weinberg, 2000; Salmon & Hall, 1994). Further, when mental training is used it is often for technical aspects and physical preparation (Cumming & Hall, 2002). It has also been reported that the imagery usually is accurate and vivid (Isaac, 1992), often more positive than negative (Hall, Rodgers, & Barr, 1990), and that athletes often use both the internal and the external perspective (Hall et al., 1998).

Table 1
Overview of studies examining performance effects following mental training in sport tasks

Study	Sport	Length	Perspective	Participants	Outcome
Shick, 1970	Volleyball	2-5 weeks	external	novices	positive **
Mendoza et al., 1978	Dart	6 days	internal	novices	positive
White et al., 1979	Swimming (start)	8 days	external	novices	positive
Mumford et al., 1985	Figure skating	4 days	both	experienced	none
Fenker et al., 1987	Am football	entire season	both	experienced	positive
Straub, 1989	Dart	5 days	internal	novices	positive
Wrisberg et al., 1989	Basketball	2 days	internal	novices	positive
Rodgers et al., 1991	Figure skating	16 weeks	internal	experienced	positive
Grouios, 1992	Spring board diving	3 weeks	not explained	experienced	positive
Blair et al., 1993	Soccer	6 weeks	both	both	positive **
Gordon et al., 1994	Cricket	3 weeks	both	both	none
Lejeune et al., 1994	Table-tennis	4 days	external	novel	positive
Pie et al., 1996	Basketball	4 weeks	both	novices	positive
Lerner et al., 1996	Basketball	entire season	both	experienced	positive **
Hardy et al., 1999	Karate	2 weeks	both	experienced	positive
Hardy et al., 1999	Gymnastics	1 day *	both	experienced	positive
Hardy et al., 1999	Rock climbing	1 day *	both	experienced	positive
Roure et al., 1999	Volleyball	2 months	both	experienced	positive
Peynircioglu et al., 2000	Basketball	1 day	internal	novices	positive
Fery et al., 2000	Tennis	1 day	internal	novices	positive
Taylor et al., 2002	Golf (putting)	1 day *	external	both	none
Smith et al., 2004	Golf	6 weeks	internal	experienced	positive
Mamassis et al., 2004	Tennis	entire season	not explained	experienced	positive
Nordin et al., 2005	Dart	1 day	both	novices	none
Brouziyne et al., 2005	Golf	5 days	internal	novices	positive
Smith et al., 2007	Field hockey	6 weeks	internal	experienced	positive
Smith et al., 2007	Gymnastics	6 weeks	internal	experienced	positive
Olsson et al., 2008a	High jump	6 weeks	internal	experienced	positive **

* no training was done, the participants only performed imagery immediately before performance.
** positive outcome on one of the measures, none on others.

An overview of intervention studies examining performance effects following mental training for a variety of sports is offered in Table 1. Taken together it shows that mental training is effective on a wide range of sports. There are however some patterns that should be more thoroughly investigated. For those studies in which mental training did *not* show any performance improvements either both internal and external perspectives had been used or only the external perspective was used. When the external perspective was used and the outcome was positive, it was often in combination with using novel participants. Another aspect that could explain some of the mixed findings is the time length of the intervention. Figure skating for example was investigated by both Mumford et al. (1985) and Rodgers et al. (1991). Both studies used experienced athletes, but the Mumford group used both internal and external perspectives, and a shorter intervention period (only 4 days compared to 16 weeks) and they did not find any performance effects of mental training. Thus, there seems to be factors, such as using internal perspective for experienced athletes, and having a sufficient time length of the intervention, that needs to be considered before using mental training. In addition to sport performance, there are several studies showing that mental training is effective on other motor tasks such as finger tapping or foot movements (Lafleur et al., 2002; Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004; Nyberg, Eriksson, Larsson, & Marklund, 2006; Olsson, Jonsson, & Nyberg, 2008b). Thus, despite some mixed findings, mental training is effective for a large variety of sports and tasks (see also, Barr & Hall, 1992; Hall et al., 1990; Munroe et al., 2000).

Brief overview of possible reasons for mixed findings

Traditionally, the tasks for which mental training would be effective have been divided into either cognitive tasks or motor tasks (Feltz & Landers, 1983). By tradition it has also been suggested that it is for the cognitive tasks in which you will find mental training to be more efficient (Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983; Perry, 1939; Sackett, 1934). Therefore, a possible reason for the effectiveness of mental training is due to that many sports, e.g. gymnastics, are cognitive in nature. However research have also found that strength exercises may benefit from using motor imagery (Ranganathan, Siemionow, Liu, Sahgal, & Yue, 2004; Yue & Cole, 1992). Hence, even though different components may be differently affected by mental training, both cognitive and motor components can be facilitated.

Type of sport has also been categorized as either open or closed (Poulton, 1957). When the environment is constant, and the movement can be performed without being interfered by the surrounding, it is referred to as a closed sport, or skill. In contrast to closed sports there are also sports classified as open. This is the case when a skill has to be performed during unpredictable environmental demands, and the individual has to adapt to the surrounding in order to perform the movement as intended. Some authors have argued that it is more beneficial to use mental training for closed rather than open sports (Coelho, Campos, Da Silva, Okazaki, & Keller, 2007; Munroe et al., 2000; Weinberg et al., 2003). Other authors have argued that closed sports should benefit more from *internal* imagery whereas *external* imagery would be more beneficial for open sports (Harris & Robinson, 1986), but the opposite has also been found (Hardy, 1997). Weinberg et al. (2003) concluded that closed sports has an advantage when using mental training since it is easier to know what to imagine, in contrast to an open sport where it is less obvious how to use mental training.

Studies have also suggested that everyone can use imagery to some extent and that individuals can choose between the external and the internal perspective based on their own choice (Hall & Martin, 1997; McAvinue & Robertson, 2008). However, there are also studies showing individual differences regarding the ability to use imagery (Kosslyn, 1999; McAvinue & Robertson, 2008). Nevertheless this has been largely neglected in research (McAvinue & Robertson, 2008) and could be a potential factor affecting the results of studies examining mental training.

GENERAL AIM

The general aim with this thesis was to further investigate how mental training affects motor performance and the underlying mechanisms of such performance change. In Study I it was taken into consideration that the internal imagery perspective seems to be the most efficient for experienced athlete, and that closed sports, with cognitive elements, seems to be the most appropriate. Therefore, a mental training program was created for high jumping and the effects both on performance and on motor parameters were investigated after a 6 week mental training intervention. In Study II we considered what previous studies have suggested about a functional equivalence between imagery and action i.e. that there supposedly is a neural overlap between imagery and action and that this is dependent of an already established motor representation. Therefore, we examined how the brain was activated during imagery of a complex task for novel and experienced participants. A combination of motor and mental training would, in an athletic context, be the most useful. Still, little is know about how a combination of motor and mental training affects motor performance and brain activity. In Study III a fingertapping task were used to test the effects on motor performance and on brain activity following a training period of a combination of motor and mental training, which was compared to using only motor training or only mental training.

I will now describe the methods used to answer these questions, and then I will give a summary of the studies.

METHODS

Neuroimaging

Functional magnetic resonance imaging (fMRI) started to be used in the early 1990s when Belliveau and colleagues (1991) generated the first functional brain maps of a visual stimulus paradigm. In their study a paramagnetic contrast was used intravenously and it was not until the discovery of the BOLD (Blood Oxygen Level Dependent) contrast fMRI got the advantage of being a non-invasive method to map functions onto the brain. The mechanisms that give BOLD an advantage over other types of contrasts are that during an increase in neural activity there will be an increase of blood flow to that given brain region, and the changes in regional cerebral blood flow (rCBF) are linearly correlated with brain activity in that region (Logothetis, Pauls, Augath, Trinath, & Oeltermann, 2001). However, due to unknown reasons the flow of oxygenated blood exceeds the oxygen consumption (Fox & Raichle, 1986). Therefore there will be a higher ratio of oxygenated blood compared to deoxygenated blood. Due to the magnetic characteristics of oxy- and deoxygenated blood the magnetic field is disturbed and the MR signal increases (for more details see e.g., Huettel, Song, & McCarthy, 2004). The BOLD contrast has been strongly correlated with brain activation in the visual system (Kwong et al., 1992), in the auditory system (Binder et al., 1994), as well as in the motor system (Rao et al., 1996). The activity is also said to reflect input and intracortical processing rather than spiking output (Logothetis et al., 2001). FMRI has good spatial resolution (millimeters), however the temporal resolution is poor (seconds). This makes it easy to pinpoint the region of activity but difficult to determine the precise timing of the activation.

After acquiring the fMRI-images a series of pre-processing steps needs to be performed to reduce the variability in the data that is not associated with the experimental task. These steps includes; slice timing to correct for time differences during image acquisition, realigning to reduce head movement artifacts, normalizing the volumes into a standard brain in terms of shape and size, and smoothing, which spreads the intensity at each voxel in the image over nearby voxels to avoid multiple comparisons problems, and misinterpretations about which voxels that are accountable for the activation. When the pre-processing steps are completed the data is ready for statistical analysis by comparing activation during different conditions in relation to each other.

In Study II, a contrast in which the brain activation during blocks of imagery of high jumping was compared to a baseline rest condition when the participants observed a fixation cross was used.

In Study III, brain activation associated with task performance was examined by contrasting the brain activation during performance of a trained (T) sequence with the activation during performance of an untrained (UT) sequence.

Video analysis

In Study I, each high jump attempt made by the participants was recorded using video cameras. To estimate the take off angle, we selected the frame when the entire foot was planted in the ground, and by using trigonometry we calculated the angle, as seen in Figure 1 (left picture). When estimating the bar clearance, we extracted the frame when the high jumper were over the bar with the hip, and measured the distance from the left shoulder to the tip of the left foot, as indicated in Figure 1 (right picture). We were then able to compare the pre-test results from the post-test results on those measures that were emphasized throughout the mental training program (explained in next section).

Figure 1. Example of images extracted from the video recordings of high jumping. Left picture shows the take off angle. The red lines show how the angle was measured. The right picture shows the bar clearance. The red line shows how the bar clearance was quantified. This was done on each attempt for each individual.

Behavioral measures

In Study I, we were interested in examining the effects of a mental training program on total high jumping performance as well as on technical aspects of a high jump (this will later be described in more details). Besides the jumping height and the number of false attempts we also looked at the bar clearance, which was defined as the bend of the back over the bar, and the take off angle, which was defined as the lean of the body away from the bar during the take off.

In Study III, we used E-prime 1.1 (Psychology Software Tools, PA, USA) to register the performance on the fingertapping task. We collected pre- and post-training performance by counting all correctly completed sequences for each of the participants on their performance outside the fMRI-scanner. Inside the fMRI-scanner we also counted the total number of correctly tapped sequences. In addition we also calculated the average total time to complete a sequence. Hence, we obtained performance measures of both the speed and the accuracy of the fingertapping performance on both the trained and the untrained sequence.

Participants

In Study I, active high jumpers were used (n=19, mean age 19.2 years). These high jumpers were recruited from a national track and field high school in Umeå. These schools offer a unique opportunity for young athletes to pursue their athletic career and at the same time obtain an education. To be selected into these programs you have to be a top promising athlete in the nation. Also active athletes from the surroundings of Umeå were included in order to increase the number of participants. By having these strict inclusion criteria we made sure that no novel high jumpers were included. This was considered important for the evaluation of the effects of mental training since there are likely to be different aspects of the effects depending on whether novices or experienced athletes are used.

In Study II, a sub-sample of the high jumpers from Study I was used (n=12 mean age 19.3 years). In addition, college students with no history of high jumping training (n=12, mean age 25.1 years) were also included. Of the 12 high jumpers included, 6 were from the group that during 6 weeks trained using a mental training program, and 6 were from the group that only maintained their regular physical training.

In Study III, since the effects of different training methods on a fingertapping task were examined, no participants with a history of playing piano, guitar, or something similar were allowed (n=30, mean age 20.3 years). Also, since we were interested in the effects of a novel task performed with the left hand only right handed participants were allowed.

All participation was voluntarily, and the studies were approved by the ethical committee at the University Hospital of Northern Sweden.

OVERVIEW OF STUDIES

Study I

Olsson, C.-J., Jonsson, B., & Nyberg, L. (2008). Internal imagery training in active high jumpers. *Scandinavian Journal of Psychology, 49(2)*, 133-140.

In this study we created an internal imagery training program for high jumping. The training program was developed with assistance of several high jumping coaches that have athletes in top world class. Since we used experienced athletes, compared to novices, we considered this to be important in order to get the necessary details of a high jump and the technical aspects high jumpers need to improve in order to jump higher. The details that the coaches especially emphasized on were bar clearance, which was defined as the bend of the back over the bar, and the take off angle, which was defined as the lean of the body away from the bar during the take off (see Figure 1). The mental training program emphasized on these details as well as the total high jump. The training program was then used on a group of active high jumpers to investigate if their jumping performance as well as technical aspects of their jumping would improve.

The procedure was divided into three parts:

(I) pre-test: all the participants were asked to jump as high as possible as if they were in a competition. We marked each attempt as well as recorded each jump using video cameras.

(II) intervention: the participants were randomly divided into either the intervention group or the control group. The training intervention lasted for 6 weeks, with two imagery sessions each week, so the total amount of imagery training was 72 minutes. During the imagery training the participants were instructed how to use the internal perspective. The participants were also given a written instruction of how to use the internal perspective during the performance of a high jump. The final description of the high jump that was given before each imagery session was:

Imagine that you are running towards the bar in a calm pace. At the curve you are slightly leaning inwards from the bar. In the last two steps the legs run past the body and you lean slightly backwards. In the take off you plant the whole foot, you feel that the knee is straight, and you lean away from the bar. The lead leg bends and is parallel with the bar, the arms help you up. The take off foot leaves the ground; you rotate so that *your back is against the bar. You pull your heals towards your head so your back bends. You push your hip up and lean your head back and pull your legs over the bar. You land on the pit and you made the jump.*

Since all the participants were active athletes both groups maintained their regular physical training. Thus, for the intervention group mental training was added on top of their physical training.

(III) post-test: the participants were again asked to jump as high as possible as if they were in a competition and the same measures as during the pre-test were recorded.

The results showed that both the control group and the intervention group indicated positive trends on all measured variables. For one variable, bar clearance, there was a significant improvement for the group that underwent the mental training program. This was not found for the group that only maintained their regular physical training. We suggested that internal imagery combined with regular physical practice improved bar clearance greater than only maintaining physical practice. Thus, it was concluded that mental training can improve complex motor components of a high jump.

Study II

Olsson, C.-J., Jonsson, B., Larsson, A., & Nyberg, L. (2008). Motor representations and practice affect brain systems underlying imagery: An fMRI study of internal imagery in novices and active high jumpers. *The Open Neuroimaging Journal*, 2, 5-13.

Due to the intense physical training by the active high jumpers used in Study I it was assumed that they would have well established motor representations of high jumping. Therefore, in the second study we wanted to examine if there would be differences in terms of brain activity when this group of participants performed internal imagery of a high jump compared to a group of high jumping novices (college students). In addition, we also wanted to examine how the mental training program used in Study I affected brain activity. Thus, we also did comparisons within the group of high jumpers between those who underwent mental training and those who only maintained their regular physical practice. When Study I was completed six of the high jumpers that did participate in the mental training group, and six of the participants that were in the control group were asked to participate in fMRI-scanning. In the scanner they were asked to repeatedly (20 times, with rest in between each attempt) imagine performing a high jump using the internal perspective. The same instructions that were used in Study I were used again in order to make sure all the participants performed the same task. In addition 12 high jumping novices were also scanned and instructed in the same way as the high jumpers.

We compared imagery to a baseline resting condition and found that the regions that were activated for the high jumpers differed significantly compared to the regions activated for the controls (see Figure 2). The high jumpers generally showed activity in motor regions such as SMA, left superior frontal gyrus, left cerebellum and bilateral pre-motor cortex. The controls, on the other hand, generally showed visual and parietal activity with regions such as left inferior parietal cortex, superior occipital cortex, left superior temporal cortex, left pre-central gyrus and right lingual gyrus activated during imagery. This suggests that novices used a third person perspective when performing the imagery task despite being instructed to use a first person perspective. In contrast, the high jumpers seemingly had no problem with the first person perspective. Moreover, when comparing the BOLD signal change for the local maxima within each cluster we found that there were two local maxima (pre-motor cortex bilaterally) in which the high jumpers had significantly stronger activity compared to the controls. Further, there was one local maximum (left superior temporal gyrus) where the controls had significantly stronger activity compared to the high jumpers, underpinning the suggestion that the controls and the high jumpers used different perspectives.

Regarding the effect of imagery training, results showed that there was a region in the left posterior parietal cortex in which the activation was greater for the high jumpers that did not take part in the mental training, as well as for the controls. We speculated that imagery training resulted in a reduction of activity for this region, which possibly could reflect that the mental training made the imagery task less cognitively demanding. Further, it was suggested that imagery training results in a more efficient motor representation that may be more easily accessed during motor performance. This is underpinned by other studies that have showed a reduction in the parietal cortex after training as a function of repeated stimulus presentation and task execution (Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2007; Raichle et al., 1994; Ungerleider, 1995).

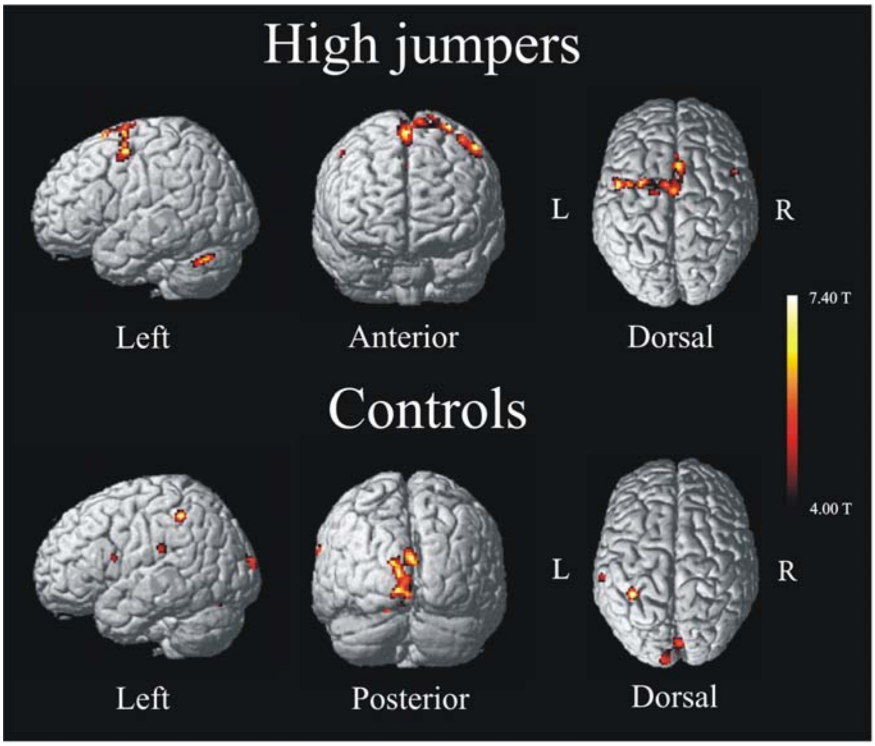

Figure 2. A rendered image showing the pattern of brain activation during imagery of a high jump contrasted to baseline rest. High jumpers, which are the top 3 brains, activated the motor system. Controls, seen in the bottom 3 brains, activated visual and parietal cortex.

In this study we were able to conclude that in order to make mental training similar to motor execution, in terms of brain activity, there must be a specific motor representation already established. Moreover, the visual activation pattern seen for the controls suggests that even though they were instructed, orally and in written form, to use internal imagery, they instead used an external perspective. We proposed that instead of feeling as if they were executing the high jump they created visual images of high jumping. Visual imagery is performed using the external perspective, and previous studies have linked visual imagery to the visual system (Ganis, Thompson, & Kosslyn, 2004; Kosslyn, Ganis, & Thompson, 2001; Kosslyn, Thompson, Kim, & Alpert, 1995). Thus, our suggestion that the controls were using the third person perspective during imagery of the high jump was underpinned. Hence, a specific motor representation is required in order to engage in internal motor imagery during mental training.

Study III

Olsson, C.-J., Jonsson, B., & Nyberg, L. (2008). Learning by doing and learning by thinking: An fMRI study of combining motor and mental training. *Frontiers in Human Neuroscience, 2(5)*.

In an athletic context it is fair to say that a combination of motor and mental training would be the most used. However, little is known about the effects on motor performance or on neural activity after combining motor and mental training. Therefore, in this study we were interested in how a combination of motor and mental training affected motor performance and brain activity. To examine this, a sequential fingertapping task was used. Specifically, the participants were instructed that each of the four fingers of their left, non-dominant, hand represented a single digit with index finger as number 1 and little finger as number 4. They were then told to, as fast and as accurately as possible, sequentially tap the fingers according to the sequence of numbers appearing on the screen. They were also instructed to continue the tapping for as long as the sequence was presented. The participants performed the tapping on a lap-top computer and we recorded each key press, giving both performance accuracy and performance speed. The sequence was shown for 30 seconds, and then followed by 30 seconds of rest, and thereafter the next sequence. This was repeated until each sequence had been shown 3 times. Two different sequences were used, A = 2 3 1 4 2 and B = 2 4 1 3 2. After pre-testing, the participants were randomly assigned one of three different training methods, motor training, mental training or combined motor and mental training.

During the training phase, the participants only trained on one of the two sequences, the other sequence only appeared during pre and post test as a control sequence. Motor training was assigned as physically performing the sequence on a table top with their hand covered by a cardboard box. Mental training was assigned as using a first person imagery perspective and mentally performing the sequence without moving the fingers. During each training session participants in either mental or motor training groups trained the allotted sequence 4 times 90s with 60s rest in between, and the training continued with 2 weekly sessions for 6 weeks. The total training time for motor or mental training was 72 minutes. For the combined motor and mental training group the training sessions consisted of first engaging in motor training according to the same instructions and the same amount of time as the motor training group. This was then directly followed by mental training according to the same instructions and the same amount of time as the mental training group. Thus, the total amount of training for the combined group was 144 minutes over six weeks.

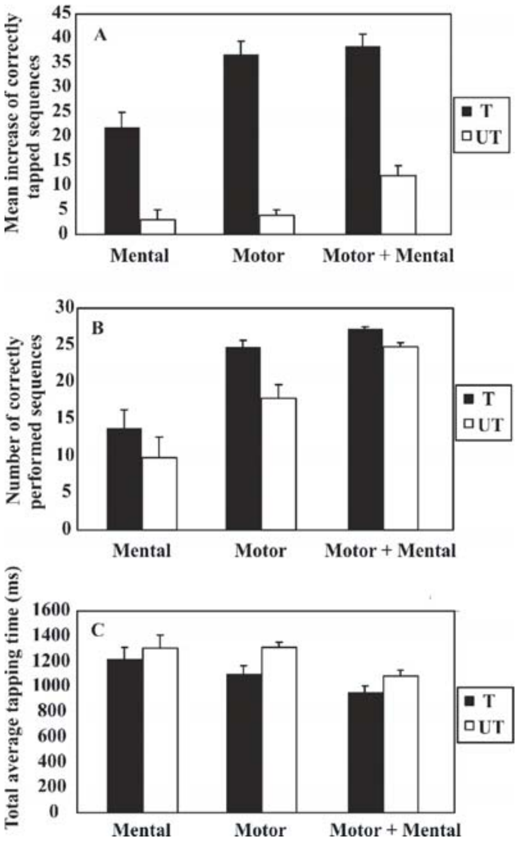

Figure 3. Tapping performance following motor, mental, or combined motor and mental training, for both the trained (T), and the untrained (UT) sequence. (**A**) shows the increase in tapping performance outside the scanner, (**B**) shows the mean number of correctly tapped sequences during fMRI-scanning, and (**C**) shows the average tapping time during the scanning. As seen all three different measures revealed the same graded pattern with combined motor and mental training and motor training only more effective compared to mental training only. Also seen is the improved performance on the untrained sequences for the combined motor and mental training.

In this study, we showed that both motor and mental training improved task performance (see Figure 3). It was clear that motor training is superior to mental training. Moreover, we showed that the underlying neural mechanisms of motor and mental training differed. Mental training was more associated with activations in the fusiform gyrus of the ventral pathway (see Figure 4), suggesting that when the participants trained mentally they created a visual memory of the sequence, which was activated during the actual task performance. Motor training was associated with increased activity in the ventral pre-motor cortex (Figure 4).

For the group using a combination of motor and mental training, task performance also increased. Comparing their results to the motor training group it is clear that only a minimal, non-significant, additive effect was given from adding mental training to motor training. The neural data indicated that both regions (visual and motor) associated with only motor or only mental training underlie task performance after combining motor and mental training (Figure 4).

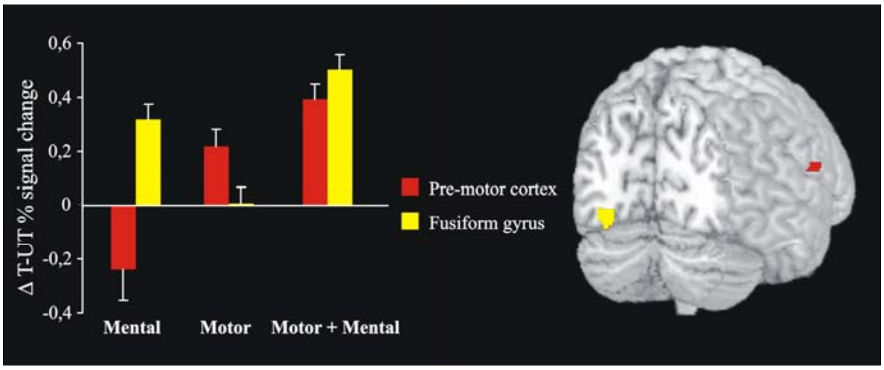

Figure 4. Sequence specific activation after 6 weeks of motor, mental, or combined motor and mental training displayed onto a rendered brain. When comparing the signal change for the trained and the untrained sequence (Δ T-UT) a significant increase was seen in the visual system following mental training and in the motor system following motor training. After a combination of motor and mental training both regions showed sequence specific activity.

The results from the control (untrained) sequence showed that neither motor training nor mental training improved task performance. Surprisingly, for the combined mental and motor training group a significant improvement was noticed even for the untrained sequence. However, since this group of participants trained according to both the motor and the mental protocols it was possible that it was not the combination of motor or mental training *per se* that gave the transfer effect, it could potentially have resulted from greater time spent training. Therefore, we added a fourth group of participants that were assigned 144 minutes of motor training. Their results did not show transfer to the untrained sequence. Thus, it was concluded that the combination of motor and mental training improved the motor flexibility and that these participants were able to decompose a new sequence into the numbers associated with the fingers, and then put them in the new order according to the new untrained sequence.

From the neural data we were able to conclude that the region involved in the transfer effect was the ipsilateral (left) cerebellum (Figure 5). Thus, we suggested that due to both cognitive and motor functions of the cerebellum (see e.g., Kelly & Strick, 2003; Thach, 2007) the motor flexibility could be enhanced. Moreover, we hypothesized that the combination of motor and mental trained improved the transformation of visual information into motor execution as well as the motor program in itself. Consequently it improved the ability for the cerebellum to select the proper motor program on basis of existing motor programs (Obayashi, 2004).

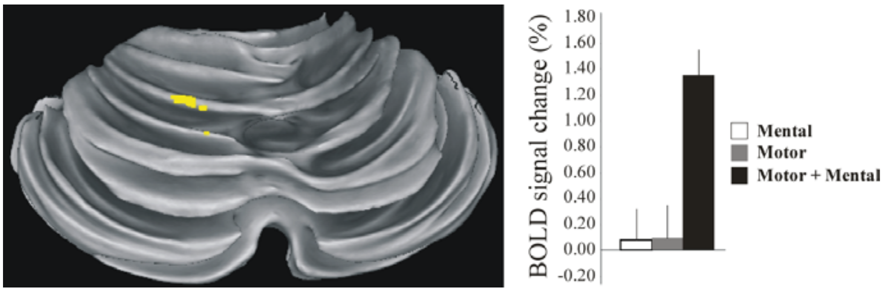

Figure 5. A rendered image of the dorsal cerebellar surface showing activity for the combined motor and mental training group performing the untrained sequence in relation to rest. The bars indicate the BOLD signal change in relation to the mean BOLD-value of the session for the three different training groups.

GENERAL DISCUSSION

This thesis presents a combination of behavioral studies of experienced athletes, neuroimaging of complex well learned skills, and controlled studies of learning novel tasks. Overall the findings support that mental training can be used to enhance motor performance, and that if a motor representation of a complex action is created physically, then imagining the action will activate motor regions. However, several critical factors that previous research has overlooked have been highlighted. These should be considered in order to understand how mental training affects motor performance. I will now elaborate upon these findings by first discussing mental training generally, then how a combination of motor and mental training is both theoretically and empirically supported, I will then finish with some practical applications and suggestions for future research.

MENTAL TRAINING REVISITED

Seidler (2004) suggested that what you learn is specific both to task and to context. Moreover, Willingham (1998) stated that motor learning occurs *if and only if* a movement is executed. These two proposals make mental training even more interesting, since somehow a mentally rehearsed task is transferred into facilitation of a motor performance. The fact that mental training is effective on motor tasks also implies that mental training to some extent is similar to motor execution. This has previously been suggested in this thesis (see introduction) and has been supported by Study II which found activity in motor regions, especially the dorsal pre-motor cortex, when high jumpers were imagining performing a high jump. The dorsal pre-motor cortex is a plausible storage spot for a high jump (Malouin, Richards, Jackson, Dumas, & Doyon, 2003; Meister et al., 2005). This region is also important to generate a final motor program (Sakai et al., 2000), and it encodes detailed plans for complex movements (Sakai et al., 2002) which are necessary in order to perform complex movements (Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004). The dorsal pre-motor cortex has also been suggested to be involved in the process of making a virtual action plan into a final motor plan (Nakayama, Yamagata, Tanji, & Hoshi, 2008). Thus, since this region was activated during imagery for the high jumpers it supports the idea that it is possible to access the motor representations of a complex skill by mental training. Moreover, the behavioral findings from Study I showed that the high jumpers participating in the mental training program improved a motor component of the high jump, the bar clearance. Thus, during mental training one can not only access motor representations by using imagery, the motor representations are also susceptible for change. However, it was also found that there are certain requirements that need to be fulfilled prior to the use of mental training, and these requirements, as you now will see, are important to consider.

Physical training

William James (1890) stated that *"the blind may dream of sights, the deaf of sounds, but the man born deaf can never imagine what sound is like, and the man born blind can never have a mental vision".* Thus, he suggested that no mental copy, of any kind, [including motor][2], will arise without prior experience. Hence, prior to mentally rehearsing actions, there must have been a physical experience of those actions. When Szpunar and colleagues (Szpunar, Watson, & McDermott, 2007) investigated the neural correlates of envisioning the future, which would be the category mental training would fall under, they found that past and future events share similar networks. However, they also found that we base future events on representations from the past, suggesting that when performing imagery of an action we do not have a representation for, the image may be clear but not taken as real. Nevertheless, authors have proposed that motor imagery relies on general representations rather than specific motor representations (de Lange et al., 2008), and that the process of imagination should not be dependent on the ability to execute movements, but rather on central processing mechanisms (Lotze & Halsband, 2006). These proposals have been underpinned by studies using individuals that have lost a limb. These studies have shown that it is possible after years of disuse to activate, via imagery, the motor regions of the lost limb. This have led to the suggestion that imagery is not affected by the physical ability to execute a movement (Hotz-Boendermaker et al., 2008; Hugdahl et al., 2001; Johnson-Frey, 2004; Johnson et al., 2002; Pavlova, Staudt, Sokolov, Birbaumer, & Krageloh-Mann, 2003). However, common to these studies is that they use individuals that previously have been able to use their arm and then lost it. Thus, it more reflects the ability of the brain to remember actions rather than creating images of actions

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[2] My interpretation of James' work on imagery and that he included motor imagery in the same category as visual and auditory.

that there are no specific representations for. Therefore, based on the finding from Study II, I suggest that in order to use the first person perspective *at all*, there must be a certain level of experience of the action. When an inexperienced athlete uses mental training he or she cannot use the internal perspective, because there are no motor representations available, instead a third perspective will be used. This would explain previous results from studies when it has been determined that athletes that are less experienced have had troubles in *"feeling"* the action and instead have "*seen"* the action in the early stages of learning. Beilock and Gonso (2008) for example may have interpreted their data differently if taking this into consideration. They examined mental training on golf-putting for novices and experienced golfers. Their conclusions were that somehow (no clear explanation was offered) only the experienced golfers were able to fine-tune the motor process during mental training but not the novices. I propose an alternate explanation i.e. the novices were not able to access the motor regions, and therefore fine-tuning the motor processes was rather difficult.

I see mainly two main reasons why researchers have failed to appreciate the difficulties of using the first person perspectives, the first is the complexity of the tasks that have been used in the studies, and the second is the specificity of the motor representation which is only obtained after intense physical training.

Task complexity

Study II used a complex task, high jumping. Even though most people are familiar with a high jump, there are not many of us that are able to perform it physically as it is done by active high jumpers. Most studies investigating neural similarities between action and imagery use simple tasks such as opening and closing of a hand, finger tapping with only one finger, or simple foot movements (see e.g., Lafleur et al., 2002; Johnson-Frey, 2004; Orr, Lacourse, Cohen, & Cramer, 2008). Szameitat and colleagues (Szameitat, Shen, & Sterr, 2007) made an attempt to address this issue by conducting a study involving the use of complex everyday tasks, such as eating with a fork and a knife. However, as I earlier reported, task complexity depends on the user (see introduction). Thus, even though the tasks in their study were complex, the individuals had no problems to perform them physically, which should indicate that there were well established motor representations present. Hence, no differentiation between experience, task complexity and motor representations could be done. Indeed, the results showed a similarity in terms of brain regions not only between action and imagery but also between complex and simple tasks. Consequently, the authors interpreted the findings such as imagery of complex tasks, in for example rehabilitation, would be useful to not only relearn previously known tasks, but also to learn new ones. In contrast, Study II showed how a complex task makes the brain activation pattern different depending on the physical experience and the corresponding motor representation.

Motor representation specificity

The second issue, although related to the first, is the specificity of the motor representations. Since all the control participants in Study II were healthy young adults, I can assume that they have a general motor program for running and jumping which would be the essential components of a high jump. Therefore, if previously suggestions about using general programs during imagery are correct, no difference should be found between controls and high jumpers. Instead, what was found was that only high jumpers were able to activate the motor system, whereas high jumping novices activated the visual and the parietal system during imagery of a high jump. I suggest that in order to activate, and possibly change, the motor representation via mental training, the individuals must have a specific motor representation for the action, a representation that they have acquired physically. In support of the idea of specificity of motor representation there have been studies showing that when expert ballet dancers were shown videos of ballet moves that were within their own repertoire motor activation was found (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Calvo-Merino, Grezes, Glaser, Passingham, & Haggard, 2006). However, when they were watching capoeira moves which, although the moves are different, are closely related to the moves they are familiar with, the motor system was not accessed.

How specific motor representations are and how that affect the motor system has been further demonstrated in a recent paper by Aglioti et al. (Aglioti, Cesari, Romani, & Urgesi, 2008). They compared a group of professional basketball players with a group of professional basketball watchers (coaches and journalists) and a group of basketball novices on a basketball judgment task. The results showed that only the highly trained athletes were able to use body cues to predict whether a basketball throw was going to be successful or not. Also, only the trained athletes were able to evoke motor excitability (measured by TMS) when watching the basketball throws. The professional watchers, even though they were familiar with basketball and watched as much basketball as the athletes played, used the trajectory of the ball to make the judgments, and did not activate motor regions. Moreover, Del Percio et al. (Del Percio et al., 2008) showed how cortical activity of experts was more focused and efficient during imagery and that this was dependent on the experience of the motor task. Other studies have shown that the brain activation during imagery is stronger for a physically trained task compared to a new task (Takahashi et al., 2005), and that novel participants process information during imagery especially in the occipital, parietal and temporal cortex to a greater extent than experts (Cremades, 2002). Thus, extensive physical practice produces a highly tuned motor system and a specificity of the motor representations, which affects the possibilities to achieve a functional equivalence between imagery and action.

Practical issues

Given that the functional equivalence between mental training and motor training is of great importance for the outcome of mental training programs (see e.g., Holmes & Collins, 2001; Jeannerod, 2006), something I will not argue against, then the level of the athlete will influence how accessible the motor representations are during mental training. Other researchers have been leaning towards the same line of reasoning. From a study by Konttinen and colleagues (Konttinen, Lyytinen, & Konttinen, 1995), for example, it was found that during good performance among rifle shooters there were different neural processes underlying the performance depending on the level of the athlete. Although all imagery-based sport-psychology models argue for the importance of functional equivalence, no general solution for this issue has been offered (c.f., Guillot & Collet, 2008; Holmes & Collins, 2001). Consequently the mental training program needs to be differently designed depending on the physical skill of the athlete. Practitioners, coaches and athletes should at least be aware of the differences it may cause when interpreting the effects of mental training (see also, Guillot, Collet, & Dittmar, 2004).

Morris and Spittle (2001) concluded that most research dealing with imagery perspectives does not enhance the understanding of how or why individuals predominantly use internal or external perspective. The same group of authors have further stated that individuals have an imagery preference towards using internal imagery (Spittle & Morris, 2007), that internal imagery should be seen as a *default* perspective, and that it is possible for each individual to choose which imagery perspective to use on his or her own (Morris & Spittle, 2001). This needs to be reconsidered and I suggest that the first person perspective should not be taken for granted at least not at the neuronal level. Also, the assumption of a functional equivalence between action and imagery is restricted to only well known actions.

A possible reason for this misinterpretation, or overconfidence in the first person perspective, may be based on the methods used when studying imagery perspective preferences. Most studies use retrospective explanations from athletes using a series of questionnaires (see e.g., Hall et al., 1990; Morris et al., 2005; Munroe et al., 2000). In these questionnaires, participants deal with several situations in which they are supposed to rate how they would perform imagery and what perspective they would use. However, these questionnaires have shown that they unlikely accurately predict which imagery perspective one would actually use in a specific occasion (Spittle & Morris, 2007). They have also shown a shortness of understanding if imagery perspective could be moderated by for example experience, skill or imagery training. When Hardy and Callow (1999), for example, investigated the effects of internal and external imagery on motor performance they found that for acquisition of a new task external was more useful, but when improving already learned tasks internal was more effective. Holmes and Collins (2001) acknowledged the difference between using external and internal perspective. However, they may have underestimated the importance of considering which neural system that is activated when using the different perspectives, and how that would affect the ability to access proper motor regions. As a result, I believe that we have to be more specific when using mental training; we cannot simply assume that individuals can use the first person perspective without prior specific physical training.

Combining motor and mental training

Task performance after mental training was associated with activation in the visual system, this was seen both for the group that engaged in mental training only, as well as for the group that trained using a combination of mental and motor training (Study III). For the combined motor and mental training group the visual activation was in addition to the activity found in the motor system, an activation that was also present after only training according to the motor training protocol. Thus, the motor sequence was represented in two distinct places of the brain, the motor and the visual system respectively, following a combination of motor and mental training.

Creating multiple representations

In a previous study comparing motor and mental training it was also found that mental training resulted in a visual representation (Nyberg et al., 2006), and that performance gains following motor and mental training were based on separate neuroplastic changes in the brain. In the Nyberg et al. study 4 days of training were used compared to 6 weeks of training used in Study III. The increase in training length resulted in different plastic changes in the brain compared to the Nyberg et al. study. In study III contralateral (right) ventral pre-motor cortex was associated with motor training and left fusiform gyrus of the visual system was associated with mental training. Nevertheless similar to the Nyberg et al. study was that mental training created a visual memory of the sequence which was responsible for the performance change following mental training. For the combined motor and mental group, however, no significant difference in performance for the trained sequence was seen compared those found for the motor training group. Therefore it is not likely that the extra visual representation, which was created from to the mental training in the combined motor and mental training group, affected task performance. Rather, it is likely that the increase in performance seen for this group was due to the representation in the motor system, since no difference were found compared to those who only used motor training.

Although combining motor and mental training did not affect task performance on the trained sequence in this study it is still important to address the issue of creating multiple representations when combining motor and mental training, and what possible effects that may have on performance. Studies support that interactions between different memory systems, and competition between systems, provides enhanced learning (Poldrack & Packard, 2003) resulting in a more robust and flexible knowledge (Ainsworth, Bibby, & Wood, 2002). Also, studies have shown that learning from multi-sensory systems is more effective compared to learning from only one sensory modality (Shams & Seitz, 2008). On the other hand, a potential downside from having mental training following motor training could be, as Luft and Buitrago (2005) suggested, that when consolidation of a task is disrupted because of a secondary task is learned immediately after it causes interference (see also, Brashers-Krug, Shadmehr, & Bizzi, 1996). However, in the case of combining motor and mental training it is not a secondary task that is learned, it is rather a secondary learning modality. Moreover, since motor and mental training share a functional overlap in situations when there is an existing motor representation it could still be facilitative. However, studies have also found that the learning modality, which would be mental or motor, not only affected the internal models (representations) but also affected the performance after learning (Schnotz & Kuerschner, 2008). Further, having multiple representations may have a negative affect on both learning and learning strategies (Ainsworth & Loizou, 2003), making it more difficult to learn/perform after having learned a certain representation (Gilmore & Green, 1984). If the creation of multiple representations following a combination of motor and mental training is facilitative for performance or if it is negatively affecting performance needs to be further addressed. Also, since study II did not show any indication of creating a visual representation for the participants with established motor representations, this may only be an issue when using combined motor and mental training on novel tasks.

Improving motor flexibility

The ability to transfer knowledge from one situation to another should be important in sport situations. Nevertheless, an important factor for transfer is probably the similarity between the learned task and the transfer task (Schmidt & Lee, 1999). Also, transfer of motor skills is usually small, and the mechanisms underpinning transfer are yet poorly understood. Wohldman et al. (Wohldmann, Healy, & Bourne, 2008) suggested that mental training alone was sufficient for motor transfer. However, the findings from Study III indicate that motor training is important to first establish a motor representation, and a general skill. Then, it may be possible using mental training to improve a more abstract representation, and also the ability to use the generalized motor program in a new situation. This has been suggested to be a possible underlying factor for transfer following motor learning (Gentner, 1983). However, an alternate explanation was offered in a study by Weigelt et al., (Weigelt, Williams, Wingrove, & Scott, 2000) when they suggested that it was not fundamental to explain transfer in terms of cognitive representations and how that would mediate improvements on transfer tasks. Rather, they suggested that it is the task structure and the performance situation that are important more so than the representation. Thus, if the physical environments of two tasks are similar, and if the goals of the two tasks are related, transfer will occur because the same type of stimuli is used, and the goal is therefore to sustain motor control in a similar manner as in the trained task. Based on how Study III was designed with two similar sequences, Weigelt and colleagues suggestion should predict transfer in all conditions. However, it was only significant for the combined motor and mental training group, suggesting that transfer is more a matter of using existing motor programs in a new way rather than picking up similar sources of information and achieve motor control.

Further support of using existing motor programs in a new way during transfer comes from a study investigating brain networks used in transfer tasks after motor training (Parsons, Harrington, & Rao, 2005). They discovered that a transfer condition increased the time individuals use to search in working memory for the motor programs they would use to plan the movements ahead. This suggests that during transfer tasks, after motor training, the already existing motor programs are used. However, it takes longer time to produce the movements, leading to minor transfer, at least when tasks are measured by either reaction times or movement times.

Based on the results from Study III the cerebellum was suggested as a structure underlying motor transfer. The transfer in this study was interpreted as an improvement of the transformation of visual information into motor execution. Research has suggested that one of cerebellum's functions may be to select the correct motor behavior in order to optimize performance (Gonzalez, Rodriguez, Ramirez, & Sabate, 2005; Penhune & Doyon, 2005) by using internal models (Iacoboni, 2001) based on already stored motor programs (Obayashi, 2004). Therefore, the cerebellum may also be used when predicting movement outcomes (Fuentes & Bastian, 2007). There are several reasons to consider the cerebellum as a plausible structure to handle motor transfer after combined motor and mental training. Using both motor and mental training strategies combines both cognitive and motor functions. As presented in the introduction, cerebellum is indeed activated both by motor action and motor imagery, leading to the conclusion of being both a motor and a cognitive structure. This is underpinned by studies showing connections of the cerebellum to both cognitive and motor regions of the brain (Kelly & Strick, 2003; Thach, 2007). Therefore I propose that the abstract representation from mental training enhances the selection of motor programs performed by cerebellum. A recent study (Seidler & Noll, 2008) also attributed transfer of motor skill to the cerebellum, even though in that particular study the task was a visuo-motor adaptation task (which are common when examining motor transfer, c.f., Krakauer, Ghez, & Ghilardi, 2005; Seidler, 2005) rather than a sequential tapping task that was used in Study III. However, the region within the cerebellum was similar to what was found in Study III and the interpretation was that the cerebellum improved the adaptation of previously acquired internal models.

Practical applications

A recent review of practical implications for mental training in sports (Guillot & Collet, 2008) suggested that up until this point there is not one set of procedures, or models that have achieved a unitary approval among practitioners. They suggested a new model in which more concern was taken on the interaction between different aspects of imagery, such as motor performance, motivation, problem-solving, and rehabilitation. However, this model, as well as others, still fails to explain why some studies of mental training do not show expected positive effects. I have in previous sections discussed how to use mental training at the representational level in order to create the best chances to facilitate motor performance. Now I turn to a methodological and practical discussion about how to evaluate mental training and how to create appropriate mental training programs.

Measures

The mental training programs used in research are usually detailed in terms of describing key components. However, in terms of interpreting the effects, there is a tendency to only look at the total performance even though there are details of the actions emphasized in the training programs. This was addressed in Study I and the decision to use more detailed outcome measures turned out successfully. This should not be surprising since previous studies have shown that it is easy to overestimate the effects of imagery even though it is known that the effects after mental training are small (Weinberg et al., 2003). That one should expect differences between the total skill and the technical measurements was further underpinned by Calmels et al. (2006) when they showed that even though the total time of a motor task can be the same regardless of whether it is imagined or executed. However, different parts of a motor task may take different time depending on whether it is performed or imagined. Thus looking at the whole skill has not only made misinterpretations about how effective imagery is, it could also possibly lead to misinterpretation about the imagery process.

Different individuals – different mental training programs

Studies have showed that most athletes engage in mental training (Hall et al., 1998; Hausenblas et al., 1999; Weinberg et al., 2003). However, as previously described there are individual differences in imagery ability and, thus, more emphasize should be taken on individualizing the mental training program instead of using a general training program. When investigating the functional networks used for poor vs. good imagers, Guillot and colleagues,(2008) suggested that even though similarities were found, there were differences as well. It appears that poor imagers recruit extra regions, mostly cerebellum, in order to compensate for being weaker at imagining. From a study, in which a mental training program with intentions to improve volleyball skills was used, also behavior effects of being a poor imager were revealed (Roure et al., 1999). After the intervention it was clear that the mental training program resulted in large individual differences in terms of performance change. These differences were possible to explain based on how successful individuals were at performing imagery. Thus, also empirically there have been suggestions of a behavioral link between imagery ability and the effects of mental training. This is yet another example of how specific one must be when creating mental training programs in order to achieve the intended results.

It is probably also not only differences in individual mental training programs and differences in imagery ability among athletes that needs to be considered. It has also been suggested that mental training should use some form of periodization that is often done with physical training (Holliday et al., 2008), with differences in the mental training program depending on whether the intention of the program is for training or for competition (Martin, Moritz, & Hall, 1999).

In this thesis it has been shown how physical training affects mental training. As a consequence the training program may have to change over time according to how the motor execution changes. With a tightly coupled use of mental training and execution the effects following mental training interventions may be improved. It has also been proposed, from a theoretical standpoint, that over time, as learning occurs and the motor representation changes, so must the content of the motor image in order to maintain the functional equivalence between imagery and action (Holmes & Collins, 2001; Kohl, Ellis, & Roenker, 1992). Empirically, however, this needs further testing.

Different sports – different mental training programs
Based on Study I it is possible to argue that imagery training is beneficial for closed sports. This has also been supported by many other studies (see introduction). For closed sports, improving and strengthening already existing motor programs would naturally be useful and therefore mental training can continue to focus on those aspects. For open sports, on the other hand, even though there are closed elements, such as a free throw in basketball, it is less clear how mental training could be useful (see e.g., Spittle & Morris, 2007). The use of combining motor and mental training (Study III) to improve the integration of new stimuli, and easier adjust to new situations could potentially be a factor for open sports. However, this may put new strains on the mental training programs and how to evaluate the effects of such intervention. Nevertheless, since previous studies have failed to find applications for the use of mental training for open sports this may be a potentially new area.

FUTURE DIRECTIONS AND LIMITATIONS

The specificity of the motor representation and its relation to mental training has been stressed throughout my thesis; however, we need to explore this further. A planned study is to measure brain activation during imagery of high jumping, stair walking, and wheelchair turning of individuals that are elite wheelchair athletes. The participants will either have acquired their injury after birth or since birth been unable to move their legs. By using these kinds of participants we will be able to evaluate the importance of prior physical experience in order to access the motor regions during motor imagery of complex tasks. It is hypothesized that even though the participants are elite athletes with advanced motor representations from extensive physical training, without prior specific physical experience of the tasks they are asked to imagine they will not access motor regions during imagery. Thus, for individuals without any history of using their legs motor activation will *only* be found for the wheelchair turning task. For the stair walking task and the high jumping task activity will be found in the visual system. For individuals that have acquired their injury after birth, motor activity will be found for the wheelchair task *and* for the stair walking task, but not for the high jumping task. Mulder et al., (2004) was also suggesting that mental training is more dependent on physical experience than previous studies have acknowledged. They proposed that without prior physical experience mental training will not be effective. At least, mental training will not be effective in the same way as when having prior physical experience. Still, no study has, as conclusively as the proposed study, been able to address this issue. Hence, with the intended design we will at least come closer to an answer about the specificity of motor representations and how that affects the use of mental training.

Possible limitations that should be mentioned with this thesis are mainly regarding the mental training program. First, one limitation is the length of the mental training program (6 weeks). Even though a similar time length has proven to be sufficient for other types of cognitive training, mostly working memory (Dahlin, Stigsdotter Neely, Larsson, Bäckman, & Nyberg, 2008; Olesen, Westerberg, & Klingberg, 2004), and that brain plasticity has been shown to appear after only 3 weeks of motor training (Hlustik et al., 2004) it could sill have limited the chances for improvements to be observed. A possible reason why longer time may have been needed in Study I is due to that the participants were experienced athletes. At the start of the training program they were already at a high level of performance, and, therefore, a longer time span may have been necessary to observe improvements at the total jumping performance. Second, another possible limitation with the training program was the use of a general mental training program. As previously suggested it is important with individualized mental training program to meet the specific needs for different individuals (c.f., Evans, Jones, & Mullen, 2004). If individualized mental training programs would have been used this may have given stronger outcomes of the intervention.

Based on the above reasoning it would be interested to thoroughly investigate the possible long term effects of mental training. It has been suggested that mental training is more efficient during skill development and that the effects fades the more experienced athletes become (Bohan, Pharmer, & Stokes, 1999). Also it was speculated that mental practice should be more susceptible to forgetting and that the effects may not be long lasting (Willingham, 1998). However, cognitive training has shown long-term maintenance 18 months after the completion of the training (Dahlin, Nyberg, Bäckman, & Stigsdotter Neely, in press). Also, it is likely that improved technique, such as observed in Study I, will translate into improved jumping height. Therefore, it would be interesting to follow individuals using a mental training program over a longer period of time, and during this time period take into consideration how to change the mental training program depending on the physical ability of the individuals.

A third interesting field for future research is the suggested improved motor flexibility after combining motor and mental training (Study III). Successive motor transformations are important in order to make behavior more functional. The production of skilled behavior relies on internal structures that have been optimized through practice. However for open sports such as in soccer, or basketball, skilled behavior does not only include mastering your own behavior, it also includes how to control movements in relation to other players. Montagne (2005) described that action plans are updated based on information given at certain time points. The information is then used to predict forthcoming events, such as when a ball is supposed to hit the ground, and in relation between the agent and the environment, so that the individual knows how to move and how to act appropriately. It was argued that this would be one of the factors discriminating between top and lower level athletes. In highly constrained tasks, such as professional soccer games, there is a high need to incorporate new information and produce fast and correct moves. Thus, if combining motor and mental training is more beneficial in terms of adjusting to new situations than only maintaining physical training, a new field of using mental training has been opened. The question is whether combining motor and mental training also increases motor flexibility in sports such as soccer, and not only in tasks involving different fingertapping sequences. Nevertheless, this is a new field of research that needs to be addressed.

CONCLUSIONS

In this thesis I have presented ideas about how mental training affects both brain and behavior. These ideas are based on empirical studies and I am therefore confident when saying that mental training can be used to improve motor performance and motor parameters. However, the specificity of motor representations has previously been overlooked, and I have shown that in order to favor a neural overlap between imagery and execution extensive task-specific physical training is a prerequisite. Also, I have presented how a combination of motor and mental training improves brain flexibility, something that may be useful in athletic contexts when adaptation to new situations appears frequently. So, next time you catch yourself imagining complex athletic actions, if your intention is to improve them, make sure you have trained them physically first. At least, that is how I would do it.

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