The relationship between motor skills and cognition in children with a special focus on spatial abilities

Inaugural-Dissertation zur Erlangung der Doktorwürde

der Philosophischen Fakultät II

(Psychologie, Pädagogik und Sportwissenschaft)

der Universität Regensburg

vorgelegt von

Jennifer Lehmann

aus Siegen

2012

Regensburg 2012

Erstgutachter: Prof. Dr. phil. Petra Jansen

Zweitgutachter: Prof. Dr. rer. nat. Mark W. Greenlee

Contents

Summary

The topic of this PhD thesis is mental rotation, the ability to imagine how an object would look like when rotated away from its original position (Shepard & Metzler, 1971), as well as the underlying motor and working memory processes in this spatial ability.

Neuroscientific research has shown that next to the intraparietal sulcus (inter alia Cohen et al., 1996) other brain areas, such as the primary motor cortex (Kosslyn, Digirolamo, Thompson, & Alpert, 1998) as well as prefrontal brain areas (Anguera, Reuter-Lorenz, Willingham, & Seidler, 2010) are also activated during mental rotation. While the involvement of motor processes has further been established on a behavioral level by inter alia Wohlschläger and Wohlschläger (1998) and Wexler Kosslyn, & Berthoz, 1998), the involvement of working memory in mental rotation is discussed controversy (Bryuer & Scailquin, 1998; Hyun & Luck, 2007). In children the involvement of motor processes in mental rotation has already been investigated (Frick, Daum, Walser, & Mast, 2009; Funk, Brugger, & Wilkening, 2005), but so far working memory processes have not been considered.

Based on the relationship between motor processes and mental rotation that has already been proven, this knowledge was to be applied in children with deficits in motor processes. While children with spina bifida show impaired mental rotation abilities (Jansen-Osmann, Wiedenbauer, & Heil, 2008), it has been shown that a manual training can improve this ability (Wiedenbauer & Jansen-Osmann, 2007). Due to the limitations of the manual training used by Wiedenbauer and Jansen-Osmann, a more motor training was considered to be more suitable.

Before the effectiveness and suitability of a motor training on mental rotation performance was investigated in children with spina bifida, the issue of the reason for the impaired mental rotation performance was investigated in more detail. While children with spina bifida show those impairments in spatial abilities, the question remains whether the impaired motor skills in children with spina bifida are responsible for the impaired mental rotation performance or whether this is due to the cognitive impairments that are associated with spina bifida and the often occurring hydrocephalus in those children. Therefore, the first experiment investigated the issue of the reason for the impaired mental rotation performance in children with spina bifida in more detail. The question, whether the impaired motor skills in those children or the cognitive impairments associated with spina bifida and the often occurring hydrocephalus in those children are responsible for the impaired mental rotation performance was addressed in the first experiment. Consequently, children with spina bifida and hydrocephalus and children with hydrocephalus only were compared regarding their mental rotation performance. It was detectable that children with hydrocephalus only performed better, apparent in faster reaction times, on mental rotation tasks than children with spina bifida and hydrocephalus. This difference was still evident when considering IQ as a covariate as well as when differentiating the aetiology of hydrocephalus. These results indicate that in children with spina bifida and hydrocephalus the impaired motor performance, associated with less mobility in early childhood and therefore less spatial experience, likely is responsible for the impaired mental rotation performance rather than the comorbidity hydrocephalus.

Based on these results it was assumed that while it seems that the impaired motor abilities are influencing mental rotation performance, a motor training should improve the mental rotation performance in those children. Consequently, the second experiment investigated the influence of motor training, respectively juggling training, on mental rotation performance in children with spina bifida. This experiment revealed a positive effect of an 8 week juggling training on the mental rotation performance in those children. The improvement was shown in a decrease in reaction times from pre- to post-test. This decrease was significant for the experimental group whereas the control group showed no such decrease. Additionally, the long term effects of such training were investigated in the experimental group. The follow-up-test after a time period of six month revealed still decreased reaction times in the three-dimensional stimuli compared to the pre-test reaction times. While it was shown that children with impaired mental rotation performance improve through motor training, no differences in these improvements were found between children sitting in a wheelchair and those who were able to walk independently.

However, the exact processes underlying this relationship between mental rotation and motor performance are still unclear. Due to the relatively rare appearance of spina bifida and the difficulties in gaining such children for research studies, we investigated the possible underlying processes of motor and mental rotation performance initially in healthy children. Based on the two previous studies the main focus of the last experiment was on the relationship of motor processes in mental rotation performance as well as the possible involvement of working memory processes in mental rotation. The results of the correlational analysis revealed a high correlation of working memory tasks with mental rotation, as well as a correlation of balance with mental rotation performance. These results indicate that it seems that rather than motor abilities, working memory skills are influencing mental rotation performance.

The results of the three experiments indicate that first of all children with spina bifida and hydrocephalus show slower mental rotation performance than children with hydrocephalus only. Secondly, it was indicated that motor training improves mental rotation performance in children with impaired spatial abilities. Furthermore, it is detected that, when considering the underlying processes for the spatial abilities, motor abilities might not play such an important role as previously assumed. Rather, it is suggested that working memory processes might play a more important role in the development of spatial abilities.

1. Preface

One of the most investigated spatial ability is the mental rotation ability, which describes the ability to mentally represent an object and to transform this object through rotation. While currently nearly 1600 studies concerning mental rotation are listed in PubMed, there are still many open questions remaining regarding the trainability of this skill in children with neurological disorders as well as the underlying processes of mental rotation.

Whereas the trainability of mental rotation with a certain amount of tasks similar to the experimental tasks used in this study involving computer or manual training has been addressed in many studies, only few studies have investigated the effects of motor training on mental rotation performance. Barely have studies considered the suitability of such motor training in daily living. In two studies with healthy adults as well as healthy children it was proven that juggling training improved mental rotation performance. Yet, the influence of such training on mental rotation performance in children with impaired spatial abilities has not been investigated up till now.

Additionally, the involvement of further processes in mental rotation performance next to motor processes has been addressed only rare. It might be that next to motor processes other processes such as working memory are also involved in mental rotation.

Therefore, information on the reasons for the impaired mental rotation performance in children with spina bifida should be added in this work. Moreover, this PhD thesis wants to contribute new insight into the trainability of mental rotation performance in children with neurological disorders, particularly spina bifida. Finally, it is tried to add new research results on the underlying and involved processes in mental rotation regarding working memory.

2. Theoretical background and state of research

This subsequent chapter will give a short introduction on mental rotation in a superior framework of spatial abilities, followed by a more precise contribution to the topic of this doctor thesis - mental rotation. This aspect is first addressed in general and subsequently explained in children, before than the topic is approached in children with neurological disorders.

In the following part, the involved processes in mental rotation are outlined. In that process, neuroscientific perspectives as well as the involvement of motor processes and working memory processes in mental rotation are considered.

2.1 Spatial abilities

In estimating distances between oneself and objects in the environment, or orientating oneself in a new surrounding, one relies on spatial abilities. These spatial abilities are necessary in everyday living and differ between individuals due to their personal requirements.

Whereas in general spatial abilities are considered to be an important component of intellectual ability, no consensus about the categorization of spatial abilities exists. One widely accepted differentiation of spatial abilities is made by Linn and Petersen (1985). In their meta-analysis they divided spatial abilities into three different categories, according to similarities in underlying processes: spatial perception, mental rotation and spatial visualisation. They defined spatial perception as the ability "... to determine spatial relationships with respect to the orientation of their own bodies, in spite of distracting information." (Linn & Petersen, 1985, p. 1482). Furthermore, mental rotation was classified as the ability to mentally rotate two- or three-dimensional figures as quickly and accurately as possible. And lastly, spatial visualization was described as the ability in which complex spatial information are manipulated when several stages are needed for solving the tasks (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). One example to assess spatial perception is the water level task, in which the subject is advised to either draw or identify a horizontal line that suits to the imaginary actual water level of the presented tilted bottle (Piaget & Inhelder, 1956). Mental rotation ability can be evaluated, for example, with the Mental Rotation Test (Vandenberg & Kuse, 1978), in which the participant has to judge which two of four presented stimuli match a reference stimuli (see Figure 1). And the spatial visualization task can be assessed with inter alia the Embedded Figure Test, in which the subjects are required to find a presented simple shape in a complex shape. Examples on how to test each of the three spatial abilities are presented in Figure 1.

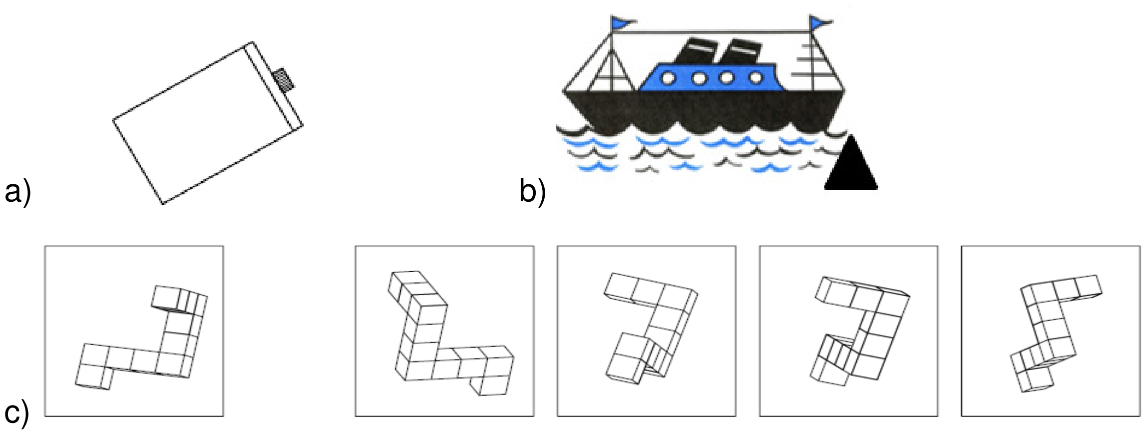

Figure 1: Examples for the measurement of the three spatial abilities. a) example of the water level task (Wiedenbauer & Jansen-Osmann, 2006), b) modified example of the Embedded Figure Test (Witkin, Oltman, Raskin, & Karp, 1971), c) example of the MRT (Peters, Laeng, Latham, & Jackson, 1995).

Spatial abilities are relevant for daily living. Particularly the mental rotation ability plays an important role. For example, mental rotation is required for problem solving (Geary, Saults, Liu, & Hoard, 2000), mathematics (Hegarty & Kozhevnikov, 1999), and science (Peters, Chrisholm, & Laeng, 1995).

The trichotomy of spatial abilities according to Linn and Petersen (1985) is widely accepted nowadays, although the differentiation between mental rotation and spatial visualization was not made before the meta-analysis of Linn and Petersen (1985).

Although spatial abilities have been matter of research since the early 19^{th} century, no consistent definitions of spatial abilities in general exist (Voyer et al., 1995). One possible explanation for classifying spatial abilities in a theoretical framework is given by Montello (1993). Spatial abilities do rather not stand for themselves, but rather are dependent on the underlying space concept to which they are brought in relation to. Montello (1993) differentiated between four spaces: figural, vista, environmental, and geographical, which are related to the human body. Whereas the figural space is smaller than the body, the vista space is as large as or even larger than the body. Both of these spaces do not need any physical movement of the perceiving body to comprehend them. The environmental space surrounds the body and cannot be explored without locomotion, for example, a neighborhood. Additionally, integration of information over a period of time is needed for this space. The last space which is differentiated is the geographical space, which is much larger than the body. This kind of space needs to be explored by symbolic representations, for example maps or models. According to this classification spatial abilities are investigated mainly in the figural space.

In conclusion, although spatial abilities are not exactly defined in general, the definition by Linn and Petersen (1985) that “spatial ability generally refers to skill on representing, transforming, generating, and recalling symbolic, nonlinguistic information” (Linn & Petersen, 1985, p. 1482), leaves behind an impression about the processes that are needed during the performance of spatial tasks.

Due to the relative independence of mental rotation compared to the other spatial abilities (Lohman, 1979), and the plainly definable construct that underlies mental rotation and that delimits it from spatial perception and spatial visualization, mental rotation applies as the most common and best investigated spatial ability. Yet, some aspects and underlying processes remain unclear and are tried to be addressed in this work. Therefore, in the next chapter mental rotation ability will be presented in detail.

Although spatial abilities and particularly mental rotation mostly produce stable gender difference effects, some studies did not find such gender effects. For example Jansen-Osmann and Heil (2007a), who used a chronometric mental rotation test, did not find such stable gender differences when investigating, for example, mental rotation speed. Whereas gender differences are most likely found when using paper pencil tests, this cannot be conveyed to chronometric measurements. Due to this inconsistency, the topic of gender differences is omitted in this PhD thesis.

2.1.1 The paradigm of mental rotation ability

According to Shepard and Metzler (1971) mental rotation is the ability to imagine how objects would look like if they were rotated away from their actual presented orientation. More precisely, mental rotation describes the ability to mentally represent spatial information which then is transferred around the three possible spatial axes.

In their study in 1971, Shepard and Metzler presented pairs of perspective line drawings on a computer screen to participants, who then had to decide whether the two presented drawings were identical or mirror reversed forms of each other. They used cube figures as stimuli, which were designed out of ten cubes that were attached to each other and which formed some arm-like structures.

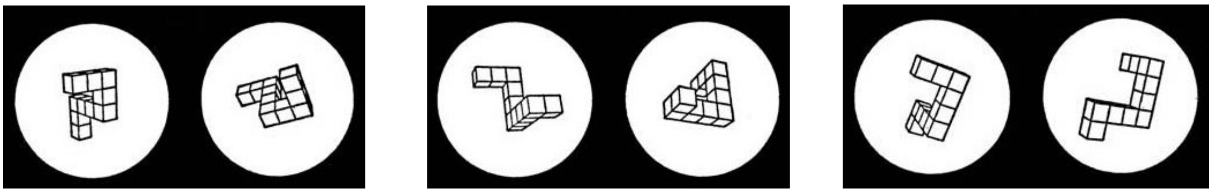

Figure 2: Examples of the different pairs of perspective line drawings used by Shepard and Metzler (1971). The pictures differ by rotation in the picture plane (left picture) and the rotation in depth (middle picture), which are both same pairs, or are mirror reversed images (right picture). Figures obtained from Shepard and Metzler (1971).

One of two presented cube figures was either rotated in the picture plane or in the picture depth compared to the other one. Additionally, the angular disparity between the two pictures increased continuously with 20°, starting at 0° and ending at 180°. While participants had to respond as fast and as accurately as possibly to the presented stimuli, reaction time and error rate were recorded. Shepard and Metzler (1971) showed that with increasing angular disparity reaction time increased as well. This increase in reaction time was linear and no differences were found between the picture plane and the picture depth condition. Based on these results, Shepard and Metzler stated that the participants had performed a process of mental rotation to achieve a same/different decision. Apart from the process of mental rotation it is assumed that other processes are involved during mental rotation as well. These processes seem to be best detected through a regression line that describes the variation of angular disparity and reaction time. The slope of the regression line indicates the speed of the mental rotation process itself. The intercept represents the processes of stimulus encoding, judgment of parity and the motor response (Cooper & Shepard, 1973). Shepard and Cooper (1982) and Heil and Rolke (2002) differentiated between several processing stages during mental rotation: perceptual processing, identification and discrimination of stimuli and identification of its orientation, mental rotation, judgment of parity, response selection, and execution. Two different models about the devolution of these subprocesses are discussed in literature. Whereas the discrete model, where one stages begins when the previous stage is finished (Sternberg, 1969), is one model, the continuous model, where one stage can operate before the previous stage has finished (Eriksen & Schultz, 1979) is another view. According to the continuous model Heil, Rauch, and Hennighausen (1998) showed that response preparation can occur during the mental rotation process. This result is in line with the findings of Band and Miller (1997), who showed that the processes of response preparation and mental rotation interfere with each other, too. Additionally, Ruthruff and Miller (1995) demonstrated an overlap of perception and mental rotation. Although Heil and Rolke (2002) demonstrated that perceptual processes seem to occur sequentially during mental rotation processes, most of the previous mentioned results indicate rather overlapping processes than sequential ones.

2.1.2 Neuroscientific research in mental rotation

During mental rotation and the underlying cognitive processes different brain areas are activated. Ark (2002) claims that the main brain areas to perform a mental rotation task are: parietal areas, some frontal, occipital and temporal components, premotor areas, somatomotor areas and basal ganglia. The process of mental rotation is apparently located in the parietal cortex. With the use of imaging technologies Cohen et al. (1996) and Jordan, Heinze, Lutz, Kanowski, and Jäncke (2001) showed activation of the intraparietal sulcus during mental rotation, namely in Broadmann´s area (BA) 7a and 7b. These findings were further supported with positron emission tomography studies, which found activation of the parietal sulcus during mental rotation as well (Harris et al., 2000). Carpenter, Just, Keller, Eddy, and Thulborn (1999) provided further evidence for the involvement of the superior parietal region in mental rotation. They investigated the activation of different brain areas considering manipulation of the amount of angular disparity. The results revealed larger activation in the superior parietal brain region under greater angular disparities. Additionally, Ark (2002) stated that in the process of mental rotation the superior parietal area plays a key role.

A meta-analysis of Zacks (2008) summed up the activated brain areas during mental rotation and supported the previous mentioned neuroimaging results. He linked the activation found in the intraparietal sulcus and the superior parietal sulcus to the hypothesis that mental rotation rests on analog spatial representations. Furthermore, he found activation of motor regions, especially in the supplementary motor areas of the precentral sulcus and the primary motor cortex, which in his understanding reflects motor stimulations during mental rotation.

While Booth et al. (2000) suggest that the mental rotated stimuli are temporally stored in working memory, for example Anguera, et al. (2010) found the evidence for the involvement of spatial working memory during the early stages in mental rotation in the activation of the prefrontal brain areas. This should be associated with the activation of prefrontal regions during mental rotation. Jordan et al. (2001) further support the assumption of the involvement of working memory processes in mental rotation. They suggest that the activation of the intraparietal sulcus found in their study maybe also reveals working memory processes, such as remembering the shape of the objects while rotating the objects. Further evidence for the involvement of visuospatial working memory in mental rotation is given by Suchan, Botko, Gizewski, Forsting, and Daum (2006). While they compared the influence of 2-dimensional and 3-dimensional stimuli on neural mechanism and the demands on working memory, their results suggested that distinct working memory processes are recruited for different stimuli types. Despite the previously mentioned findings of the involvement of working memory in mental rotation, it remains unclear how these interactions between mental rotation and working memory are constructed exactly.

Next to the activation of brain areas mentioned before the involvement of the *where (dorsal)*- and the *what(ventral)*-stream in mental rotation is considered. Whereas the where-stream, which is thought to be located from the occipital cortex to the parietal region (Mishkin, Ungerleider, & Macko, 1983), is thought to be involved in mental rotation, the what-stream, which includes the occipital region, the inferior extrastriate sulcus regions and the inferior temporal gyrus (Carpenter et al., 1999), is responsible for the perception of object identity. As mentioned before, the two different streams accomplish different functions (dorsal stream: analysis of visual movement and visual control of movement; ventral stream: perception and recognition of objects (Bear, Connors, & Paradiso, 2007) and therefore seem to be independent. But it is stated that among other things through feedback processes these two streams seems to be connected (Merigan & Maunsell, 1993). Carpenter et al. (1999) support the hypothesis that both streams are activated during mental rotation. While the dorsal stream is responsible for the mental rotation itself, the ventral stream seems to be involved in the storage of the representation of the images in the different orientation. Therefore, the two streams cannot be seen independently from each other, but are rather both activated during the processes of encoding and rotation (Koshino, Carpenter, Keller, & Just, 2005). This presumption is further supported by

Podzebenko, Egan, and Watson (2002). While they showed a primary activation of the dorsal stream with 2-dimensional stimuli, they suggest an activation of both streams when 3-dimensional stimuli are used. Therefore, the activation of dorsal and ventral streams might be dependent on the type of stimuli used. Whereas all studies allocate mental rotation to the dorsal stream, the ventral stream is suggested to be involved in the processes of object recognition and identification.

The involvement of motor areas during mental rotation is debated in research as to whether motor neurons are activated during a mental rotation task. For example Kosslyn et al. (1998) investigated the influence of two types of stimuli on the activation of motor areas in mental rotation tasks. Their results revealed that motor areas, especially primary motor cortex, premotor cortex, and posterior parietal lobe, were activated when rotation of hands were performed, whereas no such activation of motor areas was found in cube figures. Kosslyn et al. (1998) suggested that maybe different strategies are used to perform mental rotation tasks with different stimuli types and according to these strategies, different brain areas are involved in the mental rotation process. This differentiation between strategies was further supported by Kosslyn, Thompson, Wraga, and Alpert (2001), who investigated the activation of motor areas in tasks where prior to neuroimaging the participants either rotated a stimulus manually or viewed a stimulus rotated by an electric motor. Another study that supports the involvement of motor processes in mental rotation was conducted by Eisenegger, Herwig, and Jäncke (2007). They found activation of the primary motor cortex during mental rotation. The activation of motor areas was also found by Richter et al. (2000). Altogether, it can be said that during mental rotation motor areas are activated. Therefore it is indicated that not only body-related stimuli generate such activation, but abstract stimuli such as cube figures as well.

2.1.3 Motor processes in mental rotation

Whereas recent research with new imaging technologies can add to the involvement of motor processes in mental rotation, behavioral studies have postulate this involvement as well. For example Wohlschläger and Wohlschläger (1998) investigated the relationship between manual and mental rotation. They postulated a *common-processing hypothesis*, which implied that mental rotation and manual rotation should be commensurate and at the same time functionally connected. In their first experiment they investigated whether those two processes were commensurate. Therefore, they compared the reaction times for a mental rotation with the ones that were required for the manual rotation. In the mental rotation task participants had to decide as quickly and accurately as possible whether a presented stimulus matched the right or left picture of a sample stimulus by pressing the right or left button of the response apparatus. In the manual rotation participants were able to rotate the presented stimulus by turning a knob with their right hand into the position of the sample stimuli. Again they had to answer as quickly and accurately as possible by pressing the answer key with their left hand. Thereby, they were allowed to answer while still turning the knob and each participant was encouraged to use the knob although turning of the stimulus was not always necessary for solving the task. Results revealed that the reaction times in manual and mental rotation are similar. In both cases the reaction time increased with increasing angular disparity. In a second experiment the structural connection of manual and mental rotation was examined. Thus participants, which had not participated in the first experiment, had to perform simultaneously a mental rotation and a manual rotation. Thereby the manual rotation was made in the picture plane, the picture depth, or a translation movement, but only manual rotations in the picture plane interfered with the mental rotation task provided in this experiment. No influence was found on reaction times when mental rotation and manual rotation were performed in the same direction. However, reaction times increased when mental rotation and manual rotation were discordant, indicating that mental rotation and manual rotation share a common process. Based on these results, Wohlschläger and Wohlschäger (1998) saw their *common-processing hypothesis* confirmed.

A similar study was conducted by Wexler et al. (1998), who were interested in the question whether mental rotation and motor actions use same processes. Their study was based on the assumption that motor strategies, which they claimed to be external strategies, and mental strategies, which they described as the internal strategy, are somehow linked. They suggested that mental rotation is a covert manual rotation. While in a manual rotation a plan is made up and then executed, in a mental rotation the plan of the action is made up as well but rather than executed the perceptual results are simulated. To investigate this assumption Wexler et al. (1998) used an interference paradigm. Whereas in a learning phase participants practiced to manually rotate at two different speeds (45°/sec and 90°/sec), in the experimental phase they performed one speed of manual rotation while solving a mental rotation task simultaneously. More precisely, in the motor task participants turned a joystick in a clockwise or counterclockwise direction with either the slower or faster speed. Simultaneously, they solved a mental rotation task, which consisted of three different phases. In the first phase a 2-dimensional stimulus, similar to the ones used by Shepard and Metzler (1971), with an arrow pointing towards that stimulus appeared. In the second phase both, the stimulus and the arrow, disappeared and a new arrow pointing towards the planned area where the new stimulus would be shown, appeared on the screen. In the third phase the new stimulus at the indicated position appeared and the participants had to decide whether this stimulus was a rotation of the first one or a mirror reflection. Thereby speed was counterbalanced across participants. The results indicated that compatible manual and mental rotation resulted in faster reaction times and fewer errors, whereas in the incompatible condition reaction times decreased. Additionally, Wexler et al. (1998) could demonstrate that speed had an influence on mental rotation; the slower speed in manual rotation slowed down the mental rotation and the faster speed quickened the manual rotation. These results provide further evidence for the use of motor processes in mental rotation.

Furthermore, Wohlschläger (2001) showed that merely the planning of hand movements interferes with mental rotation. In his experiments he explored the interference effect of a planned hand movement with mental rotation and investigated whether this interference is solely due to the planning of the hand movement. While the participants were first advised to plan a hand movement that should be executed after solving a mental rotation tasks, in the second experiment the participants had only to imagine the hand movement and not to execute it after the rotation task. The discordant direction of mental and manual rotation in the first experiment led to increasing reaction times. Due to the results in the second experiment, Wohlschläger (2001) showed that merely the planning of a hand movement interferes with mental rotation. Thus mental rotation seems to be a covert manual rotation.

Sack, Lindner, and Linden (2007) support the involvement of motor processes in mental rotation. They investigated the influence of manually rotation a wheel while simultaneously performing a mental rotation with different stimuli material. They found different interference effects for different stimulus material. While cube figures were affected by the manual rotation in the concordant and discordant condition, hand stimuli were only affected by discordant manual rotation.

The presented studies in this chapter indicate the involvement of motor processes in mental rotation. However, research needs to clarify this involvement in detail and whether there is a possible influence of other processes in this involvement as well.

2.1.4 Working memory processes in mental rotation

At the beginning of this chapter a short introduction on working memory is given whereupon the focus will be put on working memory process in mental rotation.

To maintain task-relevant information in a system while simultaneously performing a cognitive task is the characterization of working memory by Baddeley and Hitch (1974). Whereas the term "short-term memory" is thought to be one process in memory, working memory is thought to comprise multiple factors that can integrate different processes. For example, while the short-term memory holds information, like a phone number, working memory integrates the different cognitive processes that are needed to find paper and pencil to write this number down (Gerrig & Zimbardo, 2008). The active integration of different cognitive processes is the distinction of working memory from short-term memory.

When looking into working memory one needs to distinguish between different models that describe working memory. While the working memory model of Baddeley (1992, 2000) is probably the most popular one, other authors have different suggestions for the involved processes. One example for a working memory model is the embedded-process model by Cowen (1999). His definition of working memory comprises cognitive processes which contain information that are suitable to accomplish any task which involve a mental component. Therefore he based his model on a hierarchic arrangement of long-term memory, the activated memory, and the information that is currently in the focus of attention or conscious awareness. Another description of working memory is given by Engle, Kane, and Tuholski (1999), who see working memory as a store in form of the long-term memory that is activated above threshold, as processes that achieve and maintain this activation, and as controlled attention. Additionally, they take individual differences into consideration of the working memory. Apart from the previously mentioned working memory models, one can find further models of working memory. However, the most influential model which is brought into consideration in most research studies is the multiple-component model by Baddeley (1992, 2000). The model consists of four subcomponents: the central executive with the two slave systems, the visuospatial sketch pad and the phonological loop, and the episodic buffer. The purpose of the central executive comprises attention, control of action, and problem solving and therefore the central executive regulates authoritarian functions (Baddeley, 1996). The two slave systems, the visuospatial sketchpad and the phonological loop, are responsible for manipulation and preservation of domain-specific information (Gathercole, Pickering, Ambridge, & Wearing, 2004; Meyer, Salimpoor, Wu, Geary, & Menon, 2010). Eventually, the episodic buffer fulfills the purpose of storage and integration from the two slave systems and the long term memory (Baddeley, 2000).

Whereas from neuroscientific research references for the involvement of working memory in mental rotation due to the activation of brain areas exists (Anguera et al., 2010; Booth et al., 2000; Jordan et al., 2001; Suchan et al., 2006; compare chapter 2.1.2), it still remains unclear whether all parts of the working memory are involved in mental rotation or whether only specific components such as the visuospatial sketchpad are involved. This discrepancy in science regarding the role of working memory and particularly the one of the visual spatial working memory, in visual imagery in general and more precisely in mental rotation, was shown by Zimmer (2008). Logie (2003) adds to this topic with his suggestion that there might be an additional mental workspace apart from visual spatial working memory that is responsible for the temporary storage and manipulation of visual imagery. Due to the suggested functions of this mental workspace one might assume that it would suit perfectly to mental rotation processes, but the proof is lacking.

Only few researchers have addressed the question about the relationship of the different working memory components and mental rotation ability. Hyun and Luck (2007) investigated the involvement of working memory in mental rotation of letters in adults. While they detected the involvement of the object working memory system during the mental rotation of letters, they failed to find the involvement of the spatial working memory system. Therefore it seems that the information needed for the mental rotation is stored in the object system, even though the task per se needs a spatial manipulation.

The interference of parts of working memory in a mental rotation task was investigated by Bruyer and Scailquin (1998), too. They used dual-task paradigms to examine the influence of articulatory and spatial suppression on mental rotation performance. While they found no effect of articulatory suppression on performance on the main task, they did find an effect of the spatial suppression, but interestingly, this effect was limited to the 0° condition, where no mental rotation is needed. Based on these results they suggested that the phonological loop is not involved in mental rotation or imagery tasks respectively. Furthermore, Bruyer and Scailquin (1998) found an even higher interference effect of the central executive with imagery rotation than with spatial suppression. These results suggest that next to the visuospatial sketchpad the central executive with it attentional resources might play an important role in imagery rotation as well. Whereas Bruyer and Scailquin (1998) deny an involvement of the phonological loop in mental rotation, other studies might indicate such an involvement. Due to the different possible strategies that can be used to solve a mental rotation task, for example a verbal strategy (Ramirez, Gunderson, Levine, & Beilock, 2012) or a piecemeal strategy (Jordan, Wüstenberg, Heinze, Peters, & Jäncke, 2002), the phonological loop might be involved.

Based on the little evidence for the involvement of working memory processes in mental rotation from non-neuroscientific studies, one might be able to draw conclusions for this connection on the basis of the underlying processes. While during mental rotation different processing stages occur (compare Heil & Rolke, 2002), the information of the particular stage needs to be maintained to have recourses to the information during the next stage. This is exactly what Baddeley and Hitch (1974) describe in their definition of working memory, in which information needs to be maintained while other cognitive tasks are performed. Further evidence for this connection might be detectable through the purpose of the visual spatial sketchpad. The visual spatial sketchpad is connected with the manipulation of visual images. The manipulation of objects is also done in mental rotation, where an active processing of the to-be-rotated stimulus needs to be done to solve the task.

Whereas the previous considerations indicate a relationship between working memory and mental rotation, this has to be established in further investigation, in neuroscientifical studies as well as in behavioral studies.

2.2 Mental rotation ability in children

After the general description of mental rotation in the first chapter, the following chapter comprises a more specific consideration of mental rotation and the underlying processes in children. Initially, mental rotation and neuroscientific research of this topic related to children is addressed, whereupon then motor processes and the relationship between mental rotation and motor abilities in children are regarded. In conclusion, the influence of working memory processes in mental rotation are thematised.

Initial deliberations about mental rotation in children have been made by Piaget and Inhelder (1971). They claimed that only in children aged 7 to 8 years the ability of kinetic imagery appears. According to their view children are only able to represent static imagery before that point of time. While it seemed that several studies done by Piaget and Inhelder support their position, other authors claim that inter alia the utilization of measurements with a great range of subjective interpretation as well as the manner of instructions that were given might have influenced their results and interpretations (Mamor, 1975).

One of the first studies with mental rotation that was implemented with children was done by Mamor (1975). She considered the question at what age children are capable of representing movement in imagery. Therefore she investigated 5- and 8-year-old children with a mental rotation task. Her results indicated that both, the 5- and the 8-year-old children, used kinetic imagery to solve the task. The linear increase in reaction time proportional to the angular disparities that was found by Shepard and Metzler (1971) for adults was reproduced in this study for children. When considering the speed of mental rotation in Marmor´s study, it was shown that the younger children mentally rotated at an inferior speed, namely 67°/sec, whereas the older children rotated as fast as some adults (167°/sec). These findings challenged the assumptions of Piaget and Inhelder (1971) and suggested that already children at the age of 5 years are capable of kinetic imagery. A further study of Mamor (1977) provides supplementary results that challenge the theory of Piaget and Inhelder (1971). In this study Mamor used bears and cones as stimuli material in a mental rotation task that was performed by 4- and 5-year old children as well as adults. The use of kinetic imagery was shown for children as young as 4-years of age, and therefore it can be assumed that already at this early age children are capable of performing mental rotation. However, when comparing speed of mental rotation, it appeared that the speed increased with age: 4-year old children rotated at approximately 37°/sec, 5-year old children at 84°/sec and adults rotated at 240°/sec. The slower rate of mental rotation speed in younger children compared to adults was also approved by Kosslyn, Margolis, Barrett, Goldknopf, and Daly (1990). They confirmed further that children at the age of 5-years are capable of performing mental rotation. The speed of mental rotation in children was also investigated by Kail, Pellegrino, and Carter (1980), who showed developmental changes in mental rotation speed. While they investigated 3, 4, and 6 graders as well as college students, they detected an increase in mental rotation speed with increasing age. This increase nearly doubles between the ages of 3 and 4 graders (about 143°/sec) and adults (about 250°/sec). Therefore, it seems that mental rotation ability is subjected to developmental changes.

Estes (1998) supplies evidence for the awareness of the mental activity in children. He investigated 4-, 5-, and 6-year-old children as well as adults regarding their awareness of mental rotation processes. Participants were presented with pictures of monkeys where they had to decide whether these monkeys were the same or different. While not explicitly asked to perform mental rotation, 6-year-olds and adults used mental rotation for solving the task. This was reflected in the reaction time patterns as well as in the verbal reports of the participants. Additionally, in some 4- and 5-year-old children the awareness of performing mental rotation was present, likewise detectable in the reaction time and error rate patterns, whereas in some of these children the awareness was not present.

Interestingly, even infants are able to perform mental rotation. Moore and Johnson (2008) accomplished a study with 5-months-old infants regarding their ability to mentally rotate visual stimuli in 3-dimensional space. Measurement of mental rotation ability in infants is made through fixation times, which are then compared for similar and mirror images. Moore and Johnson showed that indeed infants at the age of 5-months can perform mental rotation. This was established through the longer fixation times for the mirror images. Fascinatingly, they found this effect only for male infants but not for female infants.

More critically seen is the aspect of mental rotation in children by Newcombe and Frick (2010). They suggest that due to the paradigm used in infants, one might not be able to speak of mental rotation, but more likely of a continuation and exploration of a presented movement. Furthermore, they suggest that mental rotation in children is present in a more precursory form that shows remarkable development till middle childhood. Therefore Newcombe and Frick are not persuaded that children as young as suggested by Mamor (1975, 1977) are really able to perform mental rotation.

Additionally, they see a close link between mental rotation and motor development, which might assist in the development of mental rotation ability.

There is evidence for the capability of mental rotation in children as young as 4 years for adapted classical mental rotation tasks similar to the ones used by Shepard and Metzler (1971). Other influences of children´s development on the mental rotation ability have been focus of research as well, for example motor development (Newcombe & Frick, 2010). Therefore the next chapter initially focuses on neuroscientific results in the research in mental rotation in children before then the relationship of motor processes on mental rotation is addresses and furthermore, in a following chapter, the influence of motor abilities on mental rotation performance is presented.

2.2.1 Neuroscientific research in mental rotation in children

The activation of parietal areas as well as some frontal and occipital activation during mental rotation has been proven in studies investigating adults (Booth et al., 2000; Carpenter et al., 1999; Jordan et al., 2001; compare chapter 2.1.3). So far only a handful of studies have dealt with neuroimaging studies in children.

Two studies have examined the activated brain areas during a mental rotation task in children with functional magnetic imaging. Booth et al. (1999) found activation of the inferior and superior parietal regions in children, which is similar to the results in adults (Booth et al., 2000) although difference occur in the distribution of this activation. The children showed a higher activation of the inferior parietal lobe in the right hemisphere, whereas the superior parietal lobe was more activated in the left hemisphere (Booth et al., 1999). While Kucian et al. (2007) detected activity in the intraparietal sulcus (IPS) during mental rotation in children and adults, this activation was weaker for children. They suggest that the stronger activation in adults in the IPS "...provide evidence for an increase in activation of the left hemisphere as a result of maturation." (Kucian et al., 2007, p. 684).

Further evidence for a similar activation pattern in children compared to adults in mental rotation tasks is given by studies with electroencephalography (EEG). Jansen-Osmann and Heil (2007b) showed that the typical amplitude modulation, which can be seen in adults during a mental rotation task, is also visible in 7- to 8-year-old children as well as in 11- to 12-year-old children. Hahn, Jansen, and Heil

(2010a, 2010b) replicated and extended the specific amplitude modulation at parietal leads observed in adults during mental rotation for 5- to 6-year-old children.

Taken together, neuroimaging studies as well as EEG studies provide some evidence for the involvement of parietal areas in mental rotation in children. Yet, it seems that throughout development this brain area play an important role in mental rotation. A detailed analysis of all underlying processes in mental rotation, however, lacks in adults as well as in children. Due to the effort of neuroscientific study designs, further evidence for processes involved in mental rotation in children can be obtained by different approaches to research, such as the relationship of motor processes in mental rotation. This is addressed in the following chapter.

2.2.2 Motor processes in mental rotation in children

Whereas the previous chapter has shown that mental rotation tasks can be solved by children as young as four years of age (Kosslyn et al., 1990; Mamor, 1975), this aspect should now be addressed under the premise of the involvement of motor processes in mental rotation in children.

One study which investigated motor processes in mental rotation in 6-year-old children and adults was conducted by Funk et al. (2005). Participants had to decide as fast and as correctly as possible whether the presented stimulus was a right or a left hand. Thereby, it was determined that forearms and hands of the participants were invisible and additionally, the position of the hands to respond to the stimuli was varied (condition 1: pressing of the key with palms down, condition 2: pressing of the key with palms up). Having a congruent condition with palm-back stimuli and palm-back condition of their hands, reaction times were faster for children and adults than having palm-back stimuli but palm-up condition for their own hands. In contrast, having stimuli with palm-up only, children benefitted from a congruent condition of their own hands, resulting in faster reaction times compared to adults, where no such effect was found. Consequently, Funk et al. (2005) stated that motor processes are linked to mental rotation and that these connections are even more apparent in children than in adults. Frick et al. (2009) supported this statement, while examining the influence of motor processes on mental rotation in 5-, 8-, and 11-year-old children and adults. They instructed their participants to perform simultaneously a manual rotation, either clockwise or counterclockwise, and a mental rotation task, which resulted in compatible and incompatible trials. Reaction times increased with increasing angular disparity for all age groups, whereas younger children showed slower reaction times. While the results revealed an effect of compatibility, reaction times in the compatible condition were faster than in the incompatible condition, interestingly, this effect was only significant for the 5- and 8-year-old children, but not for the 11-year-old children and the adults. Therefore, the authors conclude that only in younger children an interference of manually turning a wheel with mental rotation occurs, indicating that the decoupling of motor processes and mental rotation experience a shift during development.

A contrary perspective regarding the involvement of motor processes in mental rotation is given by the studies by Krüger and Krist (2009a, 2000b). In their study (2009a) they investigated the presence of a motor effect in the mental rotation of hands as stimuli in children and adults. Even though they found evidence for the use of mental rotation in both their conducted experiments, a motor effect was only found in one of the two experiments. When investigating kindergarteners, first graders and adults they found a motor effect, but this effect was least pronounced in the kindergarteners. Therefore, Krüger and Krist (2009b) suggested that "…mental transformations of body parts do not necessarily involve motor processes and that embodiment may become stronger with development rather than weaker with certain tasks." (Krüger & Krist, 2009b, p. 239).

Although it seems to be a general agreement that evidence for the involvement of motor processes in mental rotation in mostly adult studies exists, contradictory results in children, as shown by the studies of Krüger and Krist, challenge this general acceptance. Therefore it seems that further need of clarification persists about the involvement of motor processes in mental rotation, especially against the backdrop of development in children.

2.2.3 Relationship between mental rotation ability and motor abilities in children

Based on the concept of the specific relationship between motor abilities and mental rotation, a short general digression on the topic of motor and cognitive abilities in children is given in the following chapter.

Although motor development and cognitive development have mostly been investigated separately, in the last years growing agreement exists about the fundamental interrelation of these two concepts (Diamond, 2000). Thereby, the approach for this interrelationship is taken differently by neuroscientific studies, experimental, quasi-experimental and correlational studies respectively. From a neuroscientific research perspective Serrien, Ivry, and Swinnen (2007) support the thesis of a link between action and cognition with research of neural correlates. They claim that neural regions which are associated with cognitive operations may be recruited in motor tasks was well. Campos et al. (2000) presented evidence for the importance of locomotion in cognitive processes in infants, likewise suggesting a close connection between motor and cognitive development.

Further encouragement for the relationship between motor and cognitive development is given by quasi-experimental design research with children with developmental disorders (Wassenberg et al., 2005). For example, Wilson et al. (2004) investigated children with developmental coordination disorder (DCD) and healthy controls regarding mental rotation tasks. Because DCD is a disorder in which the children do not show normal development of motor abilities, they are often described as clumsy. Their results suggested that DCD children do not enlist motor imagery processes into their judgment of the mental rotation task. Additionally, Loh, Piek, and Barrett (2011) investigated children with DCD, Attention Deficit/Hyperactivity Disorder (ADHD) and children with both DCD and ADHD with regard to their cognitive abilities. While they found significant poorer perceptual reasoning abilities in the groups of children with DCD, the results suggest that rather the DCD than the ADHD is responsible for these findings, further confirming that impaired motor performance maybe is responsible for the affected cognitive abilities. In addition, Wassenberg et al. (2005), who investigated the relationship between motor and cognitive performance in 5- to 6-year-old children under the control of attention, found indeed relationships between some of the cognitive measurements and motor performance, but failed to find a global-to-global relation between motor and cognitive performance. While the study showed relations between motor performance, executive functions and working memory, it seems that this relation was not found for visual perception. However, the study showed that in 5- to 6-year-old children the development of cognitive and motor functions seem to proceed in parallel stages, both for normal and delayed developing children.

Furthermore, evidence for the relationship between mental rotation tasks and motor abilities is given by the quasi-experimental study by Jansen, Schmelter, Kasten, and Heil (2011) (compare chapter 2.3.4).

A correlational approach to this topic was made in the study by Jansen and Heil (2010), who investigated the relationship between mental rotation performance and motor performance in kindergartners. While they found a relationship between these tasks, this was restricted to motor tasks that included coordinative aspects. In addition, the children that were investigated in this study comprised only of the age range of 5- to 6-year-old children.

The relationship between motor abilities and mental rotation performance was even detected in infants. Schwarzer, Freitag, Buckel, and Lofruthe (2012) investigated the relationship of crawling with the mental rotation ability in infants. Two groups of 7-months-old children, separated in crawlers and non-crawlers, were first habituated to simplified Shepard-Metzler objects and then underwent the experimental phase. Schwarzer et al. (2012) showed that crawlers performed more successful in the mental rotation task than the non-crawlers. This was demonstrated by longer fixation times at the mirror image of the objects by the crawlers. Crawling experience, where the infants can explore their environment, seems to be associated with the infant's mental rotation ability.

Additional evidence for the relationship between motor abilities and mental rotation ability can be seen in the previous mentioned experimental studies by Frick et al. (2009) and Funk et al. (2005) (compare chapter 2.2.2), who showed the influence of manual rotation, as a motor task, and the position of hands on mental rotation performance in children. Additionally, the experimental design by Wexler et al. (1998) showed the interference effect of manual rotation on mental rotation regarding the direction of rotation (compare chapter 2.1.3).

In the following chapter a closer look will be taken at other processes that might be involved in mental rotation performance in pre-school children. There, the focus will be on the involvement of working memory processes in mental rotation.

2.2.4 Working memory processes and mental rotation in pre-school children

As previously mentioned (compare chapter 2.1.4), only few studies have addressed the involvement of working memory processes in mental rotation. Although from a neuroscientific approach evidence for this relationship seems to exist, the association between these two parts of cognition remains unclear. Even less research has been dedicated to this topic in preschool children.

Even though over the last years some researchers have focused on working memory in preschool children, studies about the involvement of working memory processes in mental rotation in preschoolers are lacking. Gathercole et al. (2004) investigated whether the model of working memory of Baddeley (1992, 2000) could be applied to children aged 4 to 15 years of age. Their results hint at the fact that the measured components of working memory, phonological loop, central executive, and visuospatial sketchpad develop with a linear increase from 4 years onward. Furthermore, they stated that the differentiation between the three components as mentioned by Baddeley can be applied to their participants as well. Gathercole et al. (2004) suggested that in children the central executive is closely linked to both the visuospatial sketch pad and the phonological loop, but that the two slave systems are comparatively independent. The findings of Gathercole et al. (2004) were extended for children of 4-years of age by a study by Alloway, Gathercole, and Pickering (2006), who showed that in children aged 4-years all working memory components are in place. Additionally, the study by Alloway et al. (2006) showed a differentiation between domain-specific components in working memory, that are responsible for storage, and domain-general components, that are responsible for the processing of information. Supplementary, Alloway, Gathercole, Willis, and Adams (2004) demonstrated the multicomponent working memory model in 4- to 6-year old children for central executive, phonological loop, and episodic buffer. Although the visuospatial sketchpad was not considered in this study, this is an additional factor in working memory. Research by Roebers and Zoelch (2005) revealed a separation of the phonological loop and the visuospatial sketch pad in children as young as 4 years of age. They were able to show that in the investigated children aged 4- to 6-years the processes in the phonological loop seem to be fully developed, whereas the processes of the visuospatial sketch are not yet fully formed. Because of that Roebers and Zoelch (2005) assume that phonological storage processes and phonological rehearsal processes already collaborate, whereas in the visuospatial sketchpad the separation of visual cache and inner scribe, as suggested by Logie (1995), has not been implemented at this age yet.

Although the general topic of working memory in young children as been addressed by some researchers, to our knowledge there is no literature or scientific report about the involvement of working memory processes in mental rotation ability in preschool children. Therefore, this topic will be addressed in this PhD thesis. It is tried to explain possible connections between the different processes with the aim to establish a new basis from which further research questions can be developed.

2.3 Mental rotation in children with spina bifida and hydrocephalus

After the description of mental rotation and the underlying processes in a more general way for adults and more precisely in children, the next chapter will focus on mental rotation in a specific population, namely children with the neurological disorders spina bifida and hydrocephalus. First of all the disease pattern will be presented, after which an exposition of the cognitive abilities and the spatial abilities / mental rotation respectively is given. This chapter will conclude with the influence of motor abilities and trainability on mental rotation in this special population.

2.3.1 Disease pattern of spina bifida

Spina bifida, also known as *Myelomeningocele*, is a neurological disease that accounts for the most common congenital malformation. By definition, spina bifida is a neural tube closure defect, in which parts of the nervous system can extravasate.

This closure defect can occur during the 4th gestation week at any point along the spine. The prevalence of spina bifida is said to be different throughout the world. Aksu (2011) stated that the prevalence and incidence are lower for Japan, whereas Great Britain is at a higher risk for spina bifida. Commonly a prevalence of 0.5% for North America and Central Europe is given. The reported prevalence in Europe is one per 1,000 births (Masuhr & Neumann, 2007). Girls are more often affected than boys.

Spina bifida can be classified into *spina bifida occulta* and *spina bifida aperta*. The mildest form of this defect is *spina bifida occulta*, which is also known as a hidden spina bifida. The osseus backward part of the spinal canal is missing, but is hidden beneath muscles and derma. Therefore, the defect is superficial not visible.

Mutations on the derma can indicate a *spina bifida occulta*. Malfunctions of the bladder control may appear initially during development and adulthood, which shows that this form of spina bifida not necessarily leads to limitations in the daily living (Aksu, 2011; Berlit, 2007).

The *spina bifida aperta* can be further divided into *Meningocele* and *Myelomeningocele*. This kind of spina bifida is characterized by an incomplete closure of the neural tube that leads to eversion of parts of the spinal cord and/or the meninges through the defect vertebral arch. In the form of *Meningocel*e the meninges are bulged and the cele and liquor are inside, but the bone marrow remains in its original position. This milder form of the *spina bifida aperta* occurs rarely with neurological malfunctions and is often overlaid with intact skin, whereas the *Myelomeningocele* often appears with neurological dysfunctions such as paraplegia symptoms with sensitive and motor malfunction and bladder and bowel control.

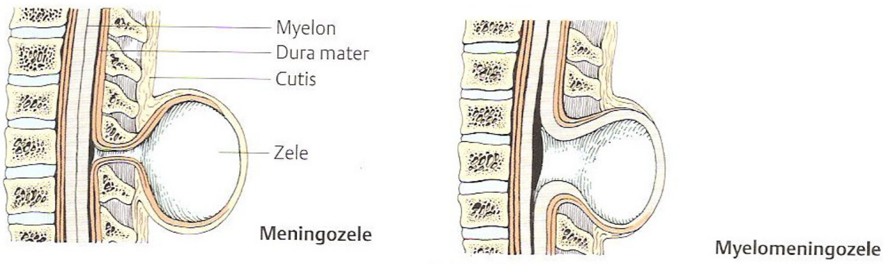

Figure 3: Description of the different kinds of *spina bifida aperta* (Figure obtained from Niethard & Pfeil, 2009, p. 262).

Myelomeningocele is the most common form of the neural tube closure defects and is associated with deformities of parts of the myelon inside the meninges (Aksu, 2011). In 80% to 90% of these cases the patients develop hydrocephalus (compare chapter 2.3.2) associated with an Arnold-Chiari malformation of the cerebellum and the hindbrain, which blocks the cerebrospinal fluid flow (Aksu, 2011; Ertl-Wagner, 2007).

The Arnold-Chiari malformation describes the displacement of the cerebellum to caudal. In children with spina bifida an intraspinal relocation of the medulla oblongata, the IVth Ventricle and parts of the cerebellum through the foramen magnum lead to a hydrocephalus. The treatment of *Myelomeningocele* with the exposed eversion of parts of the spinal cord in children takes place during the first day of life. Therefore, surgical intervention is performed to close this defect and to prevent ulceration of the spinal cord and meningitis. Due to the often coexisting hydrocephalus a shunt is placed in the first week after birth to release the pressure of the increased cerebral compression. Surgical intervention is also used in the milder forms of spina bifida to avoid traction of the cauda.

According to the level of the lesion in spina bifida, paralysis can occur in specific body areas. The degree of severity of the paralysis depends on the localization of the neural tube closure defect. The defect appears in 90% of the cases in the lumbosacral region, in 7% of the cases in the thoracolumbar region, and in 2% of the cases in the occipital regions. When only the bottom part of the spine is affected, malfunction in the muscles of the food arch can occur, which lead to only smart restrictions in walking. Defects in the lumbar region can lead to paralysis of the dorsal and plantar flexor as well as the flexor and extensor of the knee. Furthermore, complete paralysis of the lower limb can appear. Depending on the magnitude of the defect the affected children are able to walk with assistance, for example, with the support of orthesis, or do not learn to walk (Straßburg, 2008a). Additionally, malfunctions of the bladder and bowel control can arise as well as secondary deformities of the spine and joints. Therefore, after surgical intervention, an interdisciplinary approach of orthopedics, neurosurgery, physical therapy, psychology and so forth is the best approach.

The aetiopathogenesis of spina bifida is considered to be a multifactorial emergence, whereas the exact cause remains unclear. Familial disposition, genetic syndroms, and socio-economic factors are equally assumed, as well as valproic acid, fever in the precocious pregnancy, and affiliation to certain ethnic groups amongst others (Masuhr & Neumann, 2007; von Moers, 1998). The administration of folic acid “prae conceptionem” as well as in the early pregnancy has proven to be preventative efficient.

2.3.2 Disease pattern of hydrocephalus

Hydrocephalus is defined as the dilatation of the cerebrospinal fluid in the ventricles. Based on the increase of cerebrospinal fluid due to either insufficient reabsorption or defective drainage of cerebrospinal fluid, the intracranial pressure increases (Masuhr & Neumann, 2007). Different forms of hydrocephalus are distinguished according to the literature used. Throughout literature one finds the notations of communication and non-communicating hydrocephalus, congenital or acquired hydrocephalus, as well as hydrocephalus occlusus, hydrocephalus malresorptivus, hydrocephalus communicans, and normal pressure hydrocephalus (Aicardi, 2009; Masuhr & Neumann, 2007; Raabe & Steinmetz, 2011). Whereas a liquor blockade is the cause for the hydrocephalus occlusus or non-communicating hydrocephalus, the reason for a hydrocephalus communicans or malresorptivus is a defect in the liquor circulation in the subarachnoid space.

The occurrence of the Arnold-Chiari malformation in children with spina bifida leads to an occlusion of the foraminae luschkae et magendii, which implicates a blockade of the liquor and results in a hydrocephalus occlusus.

Hydrocepahlus in children without spina bifida can emerge due to multifactorial genesis. A congenital hydrocephalus can occur in form of malformations, an acquired is inter alia due to meningitis, hemorrhage, craniostenosis or a tumor.

The treatment of hydrocephalus comprises the application with a shunt to control the absorption of liquor. Associated with hydrocephalus Del Bigio (1993) stated the possibility of neuropathological changes due to the increased intracranial pressure. Thereby, the character and distribution of those changes depend inter alia on the duration and the age when hydrocephalus develops. Shunt Treatment can reduce, but not reverse the damage (for example stretching of neurons, white matter edema, delayed myelination etc.). Due to the medical progress in the early treatment of children with hydrocephalus, these children often have normal developed motor abilities. The motor abilities can be affected when next to the hydrocephalus other brain malfunctions occur (Straßburg, 2008b).

2.3.3 Development of cognitive abilities in children with spina bifida and/or hydrocephalus

Children with spina bifida tend to have a higher risk of cognitive deficits. The IQ of children with spina bifida ranges between normal and that of a minor learning disability and is therefore lower than average. This is shown in averaged IQ scores from 80 to 92. Additionally, nearly all studies show that the performance IQ of these children is lower than the verbal IQ (Jacobs, Northam, & Anderson, 2001; Lindquist, Carlsson, Persson, & Uvebrant, 2005; Wills, Holmbeck, Dillon, & McLone, 1990). Interestingly, Jacobs et al. (2001) failed to find this significant discrepancy between verbal and performance IQ in spina bifida children.

Furthermore, the cognitive abilities of children with spina bifida and hydrocephalus compared to children with hydrocephalus only seem to be similar. As mentioned before, in most of these children in both subgroups the IQs range between normal and that of a child with a minor learning disability. Concerning the IQ Lindquist et al. (2005) indicated that the range of IQ in children with spina bifida is rather homogeneous compared to children with isolated hydrocephalus, who show a greater range in their IQ scores. This might be due to the uniform cause of spina bifida, whereas the children with isolated hydrocephalus show a broader range of causes. The advantage of verbal IQ scores compared to performance IQ scores that is detectable in children with both spina bifida and hydrocephalus can also be observed in children with hydrocephalus only (Brookshire et al., 1995; Jacobs et al., 2001; Lindquist et al., 2005; Wills et al., 1990).

Beside intelligence, in form of IQ measurement, other cognitive abilities have been investigated in children with hydrocephalus with and without spina bifida. In a general approach Fletcher, Francis, Thompson, Davidson, and Miner (1992) compared the verbal and nonverbal skills in children with hydrocephalus. Thereby they investigated the influence of hydrocephalus per se on these skills independent of the etiology (aqueductal stenosis, prematurity-intraventicular hemorrhage, or spina bifida). Their results revealed that children with hydrocephalus show discrepancies in verbal and nonverbal skills, with nonverbal skills being developed worse. Due to the measurements used in their study, Fletcher et al. (1992) concluded that the results in the Judgment of Line Orientation Test (which measures the visuospatial judgment) may show spatial processing deficits in hydrocephalic children. Differences between verbal and nonverbal cognitive skills were also shown by Brookshire et al. (1995). In contrast to the study mentioned before, they explored these abilities considering the treatment of hydrocephalus, revealing that those children with shunted hydrocephalus develop poorer nonverbal than verbal cognitive abilities. Iddon, Morgan, Loveday, Sahakian, and Pickard (2004) investigated young adults with hydrocephalus and / or spina bifida on different neuropsychological measurements. They formed three matched subgroups - patients with hydrocephalus and spina bifida (SBHC), patients with hydrocephalus alone (HC), and patients with spina bifida alone (SB). Their results indicate that only the subgroups with hydrocephalus show impairments in visual and spatial recognition memory, spatial memory span, spatial working memory, and executive functioning. The subgroup with spina bifida only, however, did not demonstrate cognitive impairment in these tests. Apparently, those tests that require the integration of several cognitive processes are especially impaired in the subgroups with hydrocephalus.

While the previous mentioned studies suggest that the hydrocephalus is in particular responsible for cognitive deficits rather than the spina bifida, Lindquist, Persson, Uvebrant, and Carlsson (2008) support this assumption with their study. They investigated learning, memory, and executive functions in thirty-six children with hydrocephalus with or without spina bifida and thirty-six age- and gender-matched controls. Apart from recognition and registration skills, the children with hydrocephalus showed impaired skills regarding memory (visuospatial memory), learning (retrieval and recall of verbal and spatial material), and executive functions (visual planning, strategic thinking) independent of the etiology of hydrocephalus. Therefore, Lindquist et al. (2008) suggested that the effect of hydrocephalus on brain structures, especially on gray and white matter, increase the deficits that children with spina bifida show in cognitive tasks. Furthermore, it seems that the hydrocephalus conceals the impact of the brain malformations that develop congenitally in children with spina bifida. Additional support for this statement is given by another study conducted by Lindquist, Uvebrant, Rehn, and Carlsson (2009), where they investigated the intelligence and neuropsychological functions of children with spina bifida with and without hydrocephalus and normal controls. Their results revealed that children with spina bifida may have normal cognitive abilities compared to normal controls, whereas children with spina bifida and hydrocephalus show impaired neuropsychological functions. Based on these results Lindquist et al. (2009) support the previously mentioned assumption that the hydrocephalus very likely is the main factor that causes the cognitive deficits in children with spina bifida rather than the associated brain malformations. Thus, it seems that the cognitive outcome in children with spina bifida is dependent on the associated brain abnormalities rather than on the spina bifida itself.

It is believed that children with spina bifida and hydrocephalus and children with hydrocephalus only display deficits in visual spatial abilities due to the lower scores that they achieve in the performance IQ. These deficits can be seen in visuospatial working memory. Impaired visuospatial memory in children with hydrocephalus was shown by Lindquist et al. (2008). Although they showed deficits in visuospatial memory and executive functions for children with hydrocephalus, this has to be considered carefully because their hydrocephalus group was inhomogeneous. Hampton et al. (2011) investigated the influence of shunt-treated versus arrested hydrocephalus in children. Their results showed that children with an arrested hydrocephalus show affected neuropsychological outcomes, but perform on a higher level than children who are shunt-treated. Children with spina bifida show difficulties in visual discrimination and visual processing (Mammarella, Cornoldi, & Donadello, 2003). These findings were supported by the work of Dennis, Fletcher, Rogers, Hetherington, and Francis (2002), who documented that those deficits are more evident in action-based visual perception tasks than in object-based visual perception tasks. Based on these results, Dennis et al. (2002) suggests that object based visual perception is a process in which features are detected with regard to an allocentric frame. Furthermore, action based visual perception is a process which uses a more egocentric reference system which allows action that is visually guided and goal directed. Therefore, this process requires representations of multiple stable states and is therefore coupled to movement. In contrast, children with spina bifida show similar performance as aged-matched controls in tasks where only visual perception is required, for example, in face recognition tasks (Dennis et al., 2002). Additionally, tasks requiring ventral stream visual processing are solved better by children with spina bifida than those requiring dorsal stream visual processing. The assumption about differences in the ventral and dorsal processing stream in children with spina bifida is further supported by a study by Swain, Joy, Bakker, Shores, and West (2009), which compared children with spina bifida to healthy controls on object-based visual processing skills. Regarding the ventral visual processing pathway they found no significant differences between the two groups. Based on the results of the previously mentioned studies one can assume that the ventral processing stream is intact in children with spina bifida, whereas the performance of the dorsal processing stream seems to be impaired. Consequently, one can make the assumption that processes that rely on the dorsal processing stream might be impaired in these children. Based on the results of Podzebenko et al. (2002), who found activation of the dorsal stream during mental rotation in their study, one can draw the conclusion that, when the dorsal stream is activated during mental rotation, children with spina bifida should show deficits in mental rotation (for ventral and dorsal stream in mental rotation compare chapter 2.1.2).

While cognitive and specific aspects of visuospatial abilities have been matter of research in children with spina bifida, mental rotation has not been investigated thoroughly in this subject group. Only few studies have analyzed visuospatial abilities in children with spina bifida in detail. The classical visuospatial abilities such as spatial working memory, spatial behavior, and spatial knowledge in children with spina bifida and hydrocephalus have been investigated by Wiedenbauer and Jansen-Osmann (2006). Their results showed that children with spina bifida performed worse on all aspects of spatial cognition compared to an age-, IQ- and gender-matched control group. Additionally, to the deficits in the other measurements, the mental rotation ability in children with spina bifida is significantly worse than in the control group. Summarizing all results of the study of Wiedenbauer and Jansen-Osmann, it seems that the impairment in spatial abilities in children with spina bifida is not restricted to particular parts, but a rather substantial impairment. Another study by Wiedenbauer and Jansen-Osmann (2007) has investigated the mental rotation ability and the influence of training on this ability in children with spina bifida and hydrocephalus and healthy controls. They used a chronometric mental rotation test before and after the training to assess the reaction time and error rate of mental rotation in those children. Children with spina bifida showed impaired mental rotation abilities compared to the healthy controls. The worse performance became apparent in slower reaction times in the pretest. Whereas in the posttest both groups (spina bifida and controls) could improve their mental rotation ability, which resulted in faster reaction times, the reduction of the reaction time was twice as high for the children with spina bifida. These results indicate that children with spina bifida benefit more from a training of this ability than healthy children do.

While there has been little research on mental rotation ability in children with spina bifida and hydrocephalus, even less research has been conducted with children with hydrocephalus only. So far no study has investigated the mental rotation ability in children affected by this illness. Based on this gap in mental rotation research the question arises whether children with hydrocephalus only differ from children with spina bifida and hydrocephalus regarding their mental rotation performance. As the previously mentioned literature suggests that the deficits in cognition might be due to the brain abnormalities associated with hydrocephalus, one might assume that the two disease groups should not differ in their mental rotation performance. If other factors, for example the differences in motor abilities, are responsible for the performance in cognitive skills, the two groups might differ in their mental rotation ability. This topic will be elaborated in the next chapter.

2.3.4 Influence of motor skills on spatial abilities in children with spina bifida and hydrocephalus

The relationship between spatial abilities and motor skills in healthy children has been paid more attention to in research than in children with spina bifida and hydrocephalus. Only a handful of studies have addressed this issue.

Some research on this specific aspect has been done by Jansen-Osmann et al. (2008), who investigated the relationship between spatial cognition and motor development in the specific group of children with spina bifida and hydrocephalus. Their inquiry comprised the measurements of perception, mental rotation, spatial visualization, and spatial working memory combined with the motor abilities and the motor development of these children respectively. While they discovered that children with spina bifida performed worse in all measured spatial tasks compared to healthy controls, they found additional correlations between some of the visuospatial measurements and the age of walking. More precisely, they found correlations between visuospatial memory, the Children´s Embedded Figures Test, which assess the spatial visualization ability, and performance in a maze in children with spina bifida and their age of walking. These results indicate that there seems to be a relationship between motor development and performance on spatial tasks in these children.

This relationship has been further looked into by Wiedenbauer and Jansen-Osmann (2007). In their study they conducted a computer based motor training with children with spina bifida and investigated the effect of such training on the mental rotation ability in children with spina bifida compared to healthy controls. Before and after the manual training a chronometric mental rotation test was conducted and reaction time, error rate, and mental rotation speed was measured. While the children with spina bifida revealed slower reaction times, lower speed of mental rotation, and higher error rates in the pre-test, these differences diminished in the post-test. Whereas the reaction time gain between pre- and post-test was nearly twice as high for the children with spina bifida, the two groups did not differ in their reaction time in the post-test. Additionally, no differences between the groups were found regarding the speed of mental rotation measured with the slope of regression. Therefore it seems that the children with spina bifida improved their mental rotation process itself and not other processes like encoding or comparing after training.

Rendeli et al. (2002) have looked into the relationship between locomotion and cognitive skills in shunt-treated children with spina bifida as well. They performed neuroimaging and neuropsychological measurements to determine whether locomotion can improve cognitive development in children with spina bifida. Their results revealed a significant better achievement in performance IQ in those children that were ambulatory compared to non-ambulatory children. The authors suggest that the results could be due to the better visuomotor organization of space that the children with self-produced locomotion acquire.

As there are only few studies in children with spina bifida that investigate the relationship between motor abilities and cognitive skills, particularly mental rotation, further evidence for this relationship can be encountered in studies with children without neurological illnesses. For example, Jansen, Schmelter et al. (2011) showed impaired mental rotation ability in overweight children. They investigated motor performance and mental rotation ability in overweight children compared to healthy children and found impairments in motor as well as mental rotation performance for the overweight children. These results suggest that decreased motor abilities, which are assumed to be apparent in overweight children, influence visuospatial abilities in children. Therefore, this study provides further evidence for a relationship between motor ability and cognitive skills and mental rotation performance respectively. This assumption is also supported by studies with physically disabled children and orientation (Foreman, Stanton, Wilson, & Duffy, 2003) and in children with spina bifida in containment (Simms, 1987). Additional evidence is given by studies with children who have developmental coordination disorder (DCD). Wilson et al. (2004) showed that children with DCD solve mental rotation tasks that use pictures of hands as stimuli, in an atypical reaction time pattern compared to healthy controls. Loh et al. (2011) investigated children with DCD, Attention Deficit/Hyperactivity Disorder (ADHD), and children with both DCD and ADHD regarding their cognitive functions. Their results revealed significant poorer perceptual reasoning abilities for those groups that included children with DCD. This leads to the supposition that the deficit in visuospatial abilities in those children might be caused by the DCD and therefore, the impaired motor performance is more likely responsible for this impairment than the ADHD.

The previously mentioned studies indicate a relationship between motor abilities and cognitive skills and particularly the mental rotation ability. This relationship seems to apply to children with DCD, ADHD and overweight, as well as for children with spina bifida and hydrocephalus. Due to this general relationship the question arise whether training can influence this relationship in a positive way. Rizzo et al. (2001) delivers a possible statement for this question in postulating that children with poorer mental rotation abilities benefit more from rotation training than children with normal mental rotation ability. So far only one study has dealt with this issue in children with spina bifida and hydrocephalus. As previously mentioned Wiedenbauer and Jansen-Osmann (2008) investigated the effect of manual training on mental rotation performance in children with spina bifida. Due to the relative unsuitability of this training in daily living the research of motor training and its effect on spatial abilities in healthy children was raised.

Earlier studies of the workgroup around Jansen have already addressed this issue in healthy children and adults. They found a positive influence of motor training on mental rotation performance (Jansen, Lange, & Heil, 2011; Jansen, Titze, & Heil, 2009). Juggling was chosen to be suitable for training due to neuronal changes that have already been demonstrated by juggling training. For example Draganski et al. (2004) showed that a three-months juggling training leads to an increasing plasticity in grey matter, specifically in the mid-temporal area and the left posterior intraparietal sulcus. These structural changes occurred in exactly that brain area that is said to be involved in mental rotation (Jordan et al., 2001) (compare chapter 2.1.2). Apart from changes in gray matter, Scholz, Klein, Behrens, and Johansen-Berg (2009) expanded these results and showed changes in white-matter after juggling as well. Again it was shown that after juggling training changes in grey matter occur. Additionally, Scholz et al. (2009) revealed significant increases in white matter in the posterior intraparietal sulcus in the experimental group. Due to these neuroscientific studies the group around Jansen investigated the influence of juggling on mental rotation ability in healthy adults and children.

The positive influence of juggling on mental rotation performance was shown in a study with students (Jansen et al., 2009). Two groups (23 per group) solved a chronometric mental rotation test at the beginning and the end of a three month training period. The experimental group received one and a half hour training once a week, whereas the control group did not received such training. The results of the study revealed an improvement in reaction time for the experimental group. This effect was above the repetition effect, since a test effect was also found in the control group. The improvement in reaction time was only found for the angular disparities 90° and 180°, whereas non effect was found in the 0° condition. But since in the 0° condition no mental rotation is needed, this might explain the missing effect in this angular disparity. In an add-on study Jansen, Lange et al. (2011) expanded the previously mentioned results to school-aged children. While they compared juggling training with strengthening training in 6- to 14-year-old girls, they found only an effect on reaction time in mental rotation performance in the juggling group. Therefore, it can be concluded that the effect on mental rotation is specific to juggling training and not to a general motor training.

Based on studies regarding the relationship between motor abilities and cognitive skills in healthy and handicapped children and based on the effect of motor training on cognitive skills, one might assume that children with impaired cognitive abilities benefit from motor training regarding their impaired cognition.

2.3.5 Trainability of mental rotation ability in children

The effects of training on mental rotation ability have been thoroughly investigated in adults. Hereinafter only a few examples for studies with mental training in adults will be presented: The influence of repeated practice of mental rotation was shown inter alia by Kail and Park (1990), and Voyer (1995). Additionally, Heil, Rösler, Link, and Bajric (1998) showed the effect of practice on mental rotation. Whereas the previous studies only found specific improvement for mental rotation, Stransky, Wilcox, and Dubrowski (2010) showed that different training strategies lead to improvement in mental rotation ability. Therefore, this study showed transfer effects. Effects of motor training on mental rotation performance were shown by Jansen et al. (2009).

Whereas apart from the previously mentioned studies further research has focused on trainability of mental rotation in adults, only few studies have concentrated on children.

One of the first studies that investigated the influence of training on mental rotation ability was conducted by the before mentioned study by Mamor (1977). Half of the children received manual rotation training with seven unaligned stimuli, where either the examiner or the children manually rotated the stimuli. Mamor failed to find an influence of training on mental rotation ability. But this might not be surprising, since the training itself was relatively short and comprised only seven practice trials. In contrast to the study mentioned before, Kail and Park (1990) used a huge amount of practice trials in their study, while they investigated the influence of practice on mental rotation speed and transfer effects of practice stimuli in 11- and 20-year-old participants. In 3360 trials it had to be judge whether the presented stimuli were same or mirror reversed. Kail and Park showed that the processing times in the mental rotation tasks for children as well as adults decreased considerable over practice. No transfer effects were detected.

Sanz de Acedo Lizarraga and García Ganuza (2003) explored the influence of a two months intervention program with feedback on mental rotation performance in 14-year-old children. The intervention consisted of twelve worksheets and different model figures, which had to be worked with twice a week during lessons. Results revealed the effectiveness of the training, which showed significant gains in the experimental group compared to the control group. Furthermore, the authors showed transfer effects of the intervention on a visualization task.

Wiedenbauer and Jansen-Osmann (2008) developed a manual rotation training that they investigated regarding the influence of mental rotation ability. Participants were 64 10- and 11-year-old children who performed a chronometric mental rotation test before and after the training. The training itself consisted of 12 pairs of stimuli from which one was in an upright position and the other stimuli was to be rotated in an upright position with the help of a joystick. The whole testing and training session lasted 60 minutes. Wiedenbauer and Jansen-Osmann showed that the manual rotation training improved mental rotation ability in children. Furthermore, children in the training group showed larger difference scores in reaction times in the posttest, which indicates faster processing in the posttest. Interestingly, this study showed that the training effect was not only limited to the stimuli already presented in the pretest, but was transferred to new stimuli as well. Additionally, when analyzing the regression lines it was demonstrated that the speed of mental rotation was on an average higher for the experimental group, indicating that the mental rotation process itself experienced training.

Similar results were shown in a study with children with spina bifida likewise conducted by Wiedenbauer and Jansen-Osmann (2007). They used a similar training as previously mentioned with pre-test, training, and post-test within 60 minutes. While children with spina bifida showed impaired mental rotation ability in the pre-test compared to matched healthy controls, it showed that after training this difference decreased in the post-test. It was shown that indeed a mental rotation was performed in both groups of children, detected by increasing reaction times with larger angular disparities. Children with spina bifida revealed slower mental rotation speed, apparent in the slope of regression line, and slower other processes such as encoding, comparison etc., visible in the axis intercept. Due to the manual training both groups experienced improvement in their mental rotation ability. This became obvious in decreased reaction times, which were nearly twice as fast in the post-test compared to the pre-test in children with spina bifida. When comparing the slope of regressions in the post-test, no differences between the two groups were found, suggesting that children with spina bifida benefitted from training regarding their mental rotation speed and therefore the mental rotation process itself was improved through training rather than other processes involved. Additionally, just like in the previously mentioned study the trainings effect was not limited to learned figures, but was transferred to new stimuli as well.

As mentioned before, Jansen, Lange et al. (2011) used juggling training to improve the mental rotation ability (compare chapter 2.3.4). They revealed the positive benefit of juggling training on mental rotation performance in children and therefore, through that provided further evidence for the relationship between cognitive and motor performance.

3. Summary of the state of research

As mentioned before the relevance of mental rotation in research of spatial abilities is outstanding. Shepard and Metzler (1971) describe mental rotation as the ability to mentally represent spatial information and to transform those representations through rotation along the three axes in space. Their developed paradigm reveals that reaction times increases with increasing angular disparity. This paradigm has been investigated under a huge amount of different specifications such as gender, age, and disorders. Whereas is has been shown that healthy children as young as 4 years of age are able to mentally rotate age-appropriate stimuli, children with neurological disorders show impairments in performing mental rotation.

When considering the mental rotation performance in children with spina bifida one has to remember that this disorder is often accompanied with hydrocephalus. Research has shown that children with spina bifida show impairments in spatial abilities. This is both true for spatial abilities in general, and specifically in mental rotation (Wiedenbauer & Jansen-Osmann, 2006), as well as impaired dorsal processing (Dennis et al., 2002). Those skills might be responsible for the impaired mental rotation ability (Podzebenko et al., 2002). However, differences between children with spina bifida and hydrocephalus and children with hydrocephalus only regarding their mental rotation performance have not been made. While research on cognition does not always differentiate between hydrocephalus acquired by spina bifida or other reasons (Lindquist et al., 2008, 2009), one might need to distinguish between those disorders to reveal explanations for the impaired mental rotation performance in children with spina bifida and hydrocephalus.

Children with spina bifida and hydrocephalus and children with hydrocephalus only differ from each other due to the existing or non-existing spina bifida. Accompanied by the spina bifida are impairments in motor abilities such as impaired ambulation as well as secondary upper extremity defects and motor precision. Based on these considerations one might conclude on the one hand that due to the constrained cognitive abilities associated with hydrocephalus, for example impaired visuospatial memory and executive functions (Lindquist et al., 2008), an impaired mental rotation performance in children with spina bifida and hydrocephalus may occur. However, on the other hand these limited performances could also be attributed to the spina bifida and the associated motor disabilities. In case the motor disabilities are the cause of the impaired mental rotation performance, children with hydrocephalus without spina bifida and the associated impaired motor abilities should show a better performance in mental rotation tasks than children with hydrocephalus and spina bifida. However, provided that the impaired mental rotation performance is caused due to the occurring brain abnormality related to hydrocephalus, no difference in the performance between HC and SBHC children should emerge. This hypotheses, whether the impaired mental rotation performance in children with spina bifida and hydrocephalus is due the spina bifida or the hydrocephalus respectively, was investigated in the first quasi-experiment.

The second quasi-experiment addresses the influence of motor training on mental rotation performance in children with spina bifida. While Jansen-Osmann et al. (2008) showed impaired mental rotation abilities in children with spina bifida, Wiedenbauer and Jansen-Osmann (2007) also indicated that manual rotation training can improve these impairments in children with spina bifida. The benefit for those children regarding the manual training was nearly twice as high as the benefit in the control group, indicating that children with spina bifida benefit considerably more from training regarding their mental rotation performance. Even though the manual training proved to be successful in improving mental rotation ability, the suitability of this training was reconsidered. Preliminary considerations for choosing a suitable training were the practicability at home, the suitability for different disability levels, and the effectiveness for training the spatial abilities and mental rotation respectively.

Literature in the areas of neuroscience and behavioural science has already proven that juggling training is one successful possibility to improve mental rotation performance in the form of highly functional motor training. Due to the already successful application of juggling training in adults as well as in children (Jansen et al., 2009; Jansen, Lange et al., 2011), it was reflected whether this training could be deployed in children with spina bifida as well. Therefore, the second quasi-experiment addresses the issue of possible improvement of mental rotation performance in children with spina bifida due to a juggling training.

Based on the interesting results in the second quasi-experiment regarding the non-existing differences between children sitting in a wheelchair and children who are able to walk independently, the question arose whether further processes are involved in mental rotation. Are motor processes and therefore motor abilities responsible for the performance in mental rotation tasks? Or can one assume that, for example, working memory processes are involved in mental rotation tasks as well?

A study by Alloway, Rajendran, and Archibald (2009), who investigated working memory in four different disorders, inter alia in DCD children, can lead to this assumption. They found that children with DCD are impaired in visuospatial memory. Based on these results one might conclude that when motor impairment, as it is present in DCD, is related to poor visuospatial abilities, and visuospatial abilities are involved in mental rotation, children with poor motor abilities are impaired in mental rotation. If this is true for children with disorders, is this applicable to healthy children as well?

While in neuroscientific studies the activation of brain areas associated with working memory during mental rotation tasks is already proven, on a behavioral level this has not been investigated in detail. Therefore, the assumption of the involvement of motor processes as well as working memory processes in mental rotation on a behavioral level is addressed in the third of the three experiments in this PhD thesis.

4. Experiment 1

The first Experiment attends to the causes of the impaired mental rotation performance in children with spina bifida. It is determined whether the constrained motor abilities that are accompanied with the neural tube closure defect are causal for mental rotation performance or whether the associated cognitive restrains are responsible. Therefore, children with spina bifida and hydrocephalus, as well as children with hydrocephalus only, participated in this study and were investigated with a chronometric mental rotation test. It was assumed that similar mental rotation performance in children with spina bifida and hydrocephalus and children with hydrocephalus only indicates the influence of cognitive restrains on mental rotation. On the contrary, diverging performances between the two groups would lead to the assumption that the impaired motor abilities rather than the cognitive restrains are responsible for the mental rotation performance.

4.1 Method

4.1.1 Sample

In this study twenty-four children aged between 8 and 12 years of age took part. The children were divided into two groups: one group contained twelve spina bifida children with hydrocephalus (SBHC), the other group comprised twelve children with hydrocephalus only (HC). Whereas the children with HC were recruited through cooperation with the Neurosurgery Center of the Regensburg University Hospital, the data for the SBHC children were obtained from the entrance tests of study two, in which a training program for children with spina bifida was evaluated (Lehmann & Jansen, 2012). The experiment was conducted according to the guidelines of the ethical review committee, which was informed of the study and the experimental plan.

Based on gender, age, and cognitive processing speed the SBHC children from the study of Lehmann and Jansen (2012) were chosen to match the HC children. The children were matched according to sex ($\chi^2 < 1$ in 2×2 comparisons), age (F (1,22) = .137, *n.s.*), cognitive processing speed (F (1,22) = 2.915, *n.s.*), and diagnosis (HC vs. SBHC). The matching by cognitive processing speed was applied due to the well known effect that children with spina bifida and hydrocephalus show a slower reaction time per se.

4.1.2 Breadboard

Questionnaire:

The Questionnaire for children with spina bifida and hydrocephalus comprised statements about age, gender, juggling experience, sporting activities, medical information related to spina bifida and possible secondary diseases. Also it consisted of information regarding therapeutic treatment, school type, as well as assessments regarding the autonomy of the children. The questionnaire was completed by one of the parents of each participating child.

For children with hydrocephalus only a questionnaire similar to the one presented to the children with spina bifida was applied and only adapted to the characteristics of the disorder hydrocephalus.

Chronometric mental rotation test:

The chronometric mental rotation test (CMRT) is a measurement to assess the mental rotation ability. In that test a laptop with a 17`` monitor is used to present each participant two stimuli that have to be evaluated whether they are identical or mirror-reversed images. The experimental stimuli consisted of 18 perspective line drawings of three dimensional cube figures similar to the ones used by Shepard and Metzler (1971) and Jansen-Osmann and Heil (2007a).

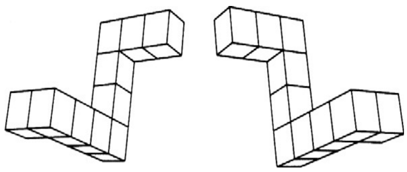

Figure 4: Example for the stimuli used in the chronometric mental rotation test (Jansen-Osmann & Heil, 2007a).

The stimuli were presented on a computer display in the approximate size of 7 cm x 7 cm. It was determined that the distance between the stimuli was to be 14 cm. Participants were allowed to choose their most comfortable viewing distance. Throughout the test two stimuli were presented at the same time on the screen. Whereas the left stimulus served as the standardized stimulus, the right stimulus was either an identical or mirror-reversed image of the left stimulus. The angular disparity between the two stimuli was 0°, 90°, or 180° in a clockwise or counter-clockwise direction.

Each participant was instructed to decide as quickly and accurately as possible whether the two stimuli were the same or mirror-reversed images. The response was given by pressing a mouse button. The left button of the mouse indicated the “same” answer; the right button indicated the “mirror-reversed” answer. To make the options clearer, each of the two response buttons was marked with either a green (left) or a red (right) sticker. The trials were set to begin with a fixation cross presented for 500 ms on a blank background. After that a pair of stimuli appeared and remained on the screen until the participant responded. Feedback was given to each participant in form of a “+” for a correct answer and a “-” for an incorrect answer. This procedure was based on the studies of Jansen et al. (2009) and Jansen, Lange et al. (2011), where likewise all participants received feedback. The feedback remained on the screen for 500 ms. The next trial was initiated after 1500 ms. The combination of objects (18 cube figures), type of response (same/mirror-reversed), and angular disparity (0°, 90°, 180°) which were presented three times, resulted in a total amount of 324 trials. To familiarize participants with each task a block of 54 unrecorded practice trials was performed at the beginning of the testing session. The experimental trials were assessed in one block with all 324 trials. The stimuli were presented with breaks after every 27th trial. Reaction time and error rates were measured for each participant. The same tasks and stimuli were used for the measurement in pre- and posttest design.

Number Connection Test:

The Number Connection Test (ZVT; Oswald & Roth, 1987) measures the cognitive speed of participants. These are advised to connect the numbers that are presented in the ascending order as fast as possible with a pen. So the test consists of four different sheets of paper for testing and an additional paper with practice examples. Whereas the practice sheet is composed out of two matrices in which the numbers 1-20 are randomly ordered, the testing sheets consists of one matrix each, in which the numbers 1-90 are presented in an irregular sequence in a matrix of nine rows and 10 columns. For each participant the time to complete the connection of all ninety numbers was measured. After completing all four testing sheets the times of all are added and divided by four. The results then were converted into IQ estimations. The correlation between the ZVT and the standard IQ test is about r = .60 - .80 (Vernon, 1993). Internal consistency and 6-month test-retest reliability is about 0.90 - 0.95. The ZVT is the equivalent to the Trail Making Test A (Reitan, 1956).

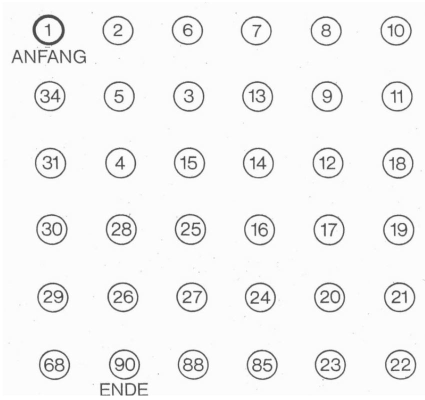

Figure 5: Example of the Number Connection Test, extract of the exercise sheet "B" (Oswald & Roth, 1987)

4.1.3 Test execution

Each participant was tested by the same principle examiner in a quiet room in their private home. Thereby, the ZVT was conducted first, after which the chronometric mental rotation test was performed by each child. The questionnaire was simultaneously given to one parent to be completed. Testing sessions lasted approximately one and a half hour.

4.1.4 Design and statistical analysis

The system SPSS 18.0 was used for the analysis of the data. Only correct responses were included in the analysis and before the statistical analysis the reaction time (RT) data was trimmed. Reaction time data more than two standard deviations above or below the mean per condition and per participant were excluded from analysis. Included in the two analysis of variance were the dependent variables "reaction time" and "error rate", the between-subject factor "group" (HC, SBH), and the within-subject factor "angular disparity" (0°, 90°, 180°).

4.2 Results

For both groups a questionnaire was used to assess general demographic information and information regarding medical condition and infantile motor development. All children in the SBHC group had a myelomeningocele and suffered from hydrocephalus. All children, but one, were treated with a shunt. The localization of the lesion was in the lumbar region in ten children and the thoracic region in two children. None of the children in the SBHC group suffered from epilepsy, uncontrolled seizure disorder, perception disorder, or behavioral disturbances. The children in the

HC group were all diagnosed with hydrocephalus. Eight of these children had congenital, respectively neonatal hydrocephalus, while the other four children had acquired hydrocephalus at the age of 7, 9, 10, and 11 years respectively. In six children with hydrocephalus the cause was a malformation, in two children the hydrocephalus developed after meningitis, in one child the cause was uncertain, in one child it occurred after hemorrhage, in one due to a craniostenosis, and in one it was due to a tumor. Whereas eight of the children with hydrocephalus were treated with a ventriculoperitoneal shunt, four of these children were treated with a ventriculostomy. In both groups 9 children were right-handed and 3 children were left-handed.

4.2.1 Reaction time

A main effect for the factors “angular disparity”, $F\,(2,44) = 64.229$, $p < .01$, $\eta^2 = .745$, and “group”, $F\,(1,22) = 7.581$, $p < .05$, $\eta^2 = .256$, and a significant interaction between “angular disparity” and “group”, $F\,(2,44) = 5.453$, $p < .05$, $\eta^2 = .199$, was found.

The existing interaction between “angular disparity” and “group” is based on the fact that there are no significant differences in both groups for the 0° condition, $F\,(1,22) = 2.43$, *n.s.*, $\eta^2 = .100$, but that there are significant differences in the 90° condition, $F\,(1,22) = 7.01$, $p < .05$, $\eta^2 = .242$, and in the 180° condition, $F\,(1,22) = 7.67$, $p < .05$, $\eta^2 = .259$ (compare figure 6). This interaction persists even when IQ is considered as a covariate ($F\,(2,42) = 7.175$, $p < .05$, $\eta^2 = .255$).

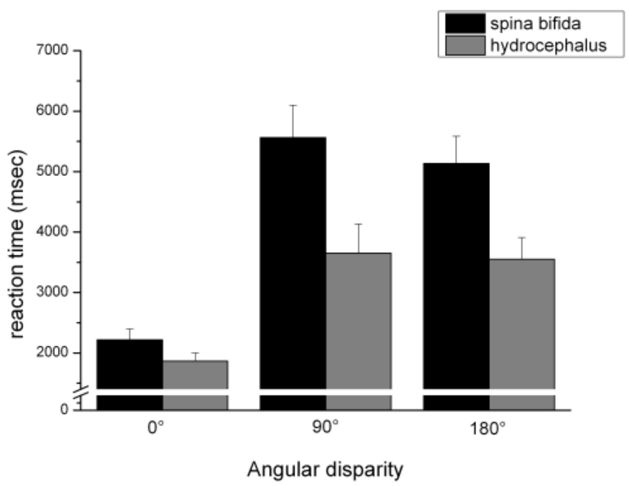

Figure 6: Mean reaction times and standard deviations (error bars) for the three angular disparities separated for the two different groups.

4.2.2 Error rate

The error rate was assessed with a repeated-measures ANOVA and revealed a significant main effect for the factor "angular disparity", F (2,44) = 65.038, $p < .01$, $\eta^2 = .747$, but no significant effect for the factor "group", F (1,22) = .201, *n.s.*, $\eta^2 = .009$. Furthermore, no interaction between "angular disparity" and "group", F (2,44) = .147, *n.s.*, $\eta^2 = .007$, was found.

Whereas the error rate increased from 0° to 90°, F (1,23) = 106.21, $p < .01$, $\eta^2 = .822$, a decrease occurred from 90° to 180°, F (1,23) = 5.54, $p < .05$, $\eta^2 = .194$, but when comparing the 0° to 180° condition an increase was noted, F (1,23) = 68.23, $p < .01$, $\eta^2 = .784$. Regarding the number of incorrect answers, an increase in the percentage across the three angular disparities was detected: in the "0°" condition 9.19% (*SE* = 6.1) of the answers were wrong, in the "90°" condition 48.61% (*SE* = 20.4) of the answers were wrong, and in the "180°" condition 41.44% (*SE* = 21.8) were wrong.

Table 1: Presented are the means and standard deviation of the error rate (%) overall and separated for each group as well as separate for the three different angular disparities

	overall	spina bifida	hydrocephalus
0°	9.91 (1.24)	8.97 (1.81)	9.41 (1.79)
90°	48.61 (4.16)	46.56 (4.18)	50.77 (7.36)
180°	41.44 (4.45)	39.82 (5.04)	43.05 (7.55)

4.2.3 Additional Results

Due to the fact that the children with SBHC all have a uniform cause of HC, namely congenital, whereas the group of children with HC show an inconsistency in the cause of HC, namely congenital or acquired HC, it was chosen to compare the data for the children with SBHC and HC only with the data for children who have congenital HC. An analysis of variance was conducted with the variables "reaction time" and "error rate", the between-subject factor "group" (HC congenital only, SBHC), and the within-subject factor "angular disparity" (0°, 90°, 180°).

The analysis of variance was comparable to the one conducted with the data from “reaction time” and “error rate” (compare chapter 4.2.1 and 4.2.2). The results of the analysis of variance with the variable “reaction time” revealed a main effect for “angular disparity”, F (2,36) = 48.084, p < .01, η^2 = .728, and “group”, F (1,18) = 7.076, p < .05, η^2 = .282, and an interaction between both factors, F (2,36) = 5.307, p < .05, η^2 = .228. Furthermore, a main effect with the variable “error rate” was found for “angular disparity”, F (2,36) = 67.568, p < .01, η^2 = .790. No main effect for “group”, F (1,18) = 1.840, *n.s.*, η^2 = .093, nor an interaction between “group” and “angular disparity”, F (2,36) = 1.108, *n.s.*, η^2 = .058, was found.

4.3 Discussion

The present study investigated the mental rotation ability of children with hydrocephalus, both with and without spina bifida, on a three-dimensional mental rotation task. Children with both spina bifida and hydrocephalus (SBCH) showed reduced mental rotation abilities compared to children with hydrocephalus only (HC). This was revealed by slower reaction times in the rotated conditions. This difference remained consistent even when IQ was included as a covariate.

Our findings are different to those of Iddon et al. (2004), who found impairment in visual and spatial cognition in children with hydrocephalus compared to children with spina bifida. However, they found no differences between the two subgroups SBHC and HC. Lindquist et al. (2008) detected no differences in performance on visuospatial tasks between children with both myelomeningocele and hydrocephalus and children with hydrocephalus only. This suggests that the hydrocephalus itself may be the cause for the impairment and not the myelomeningocele. Additionally, Lindquist et al. (2009) did confirm the results from their previous study. They compared children with spina bifida with and without hydrocephalus to normal controls and found that the children with spina bifida only did not differ from normal controls in their neuropsychological functions, whereas those with both spina bifida and hydrocephalus did differ. While the results found by Lindquist´s group accounts for their specific neuropsychological testing, which did not include a mental rotation assessment, their study does not support our findings regarding the mental rotation ability. It seems that while the more general measurements used in the previously mentioned studies do not show differences between SBHC children and HC children, a more precise measurement of one specific spatial task does show differences between those two groups. Even when considering the etiology of hydrocephalus in this study, differences in mental rotation performance exist. The different etiology of hydrocephalus is considered due to the fact that the cause of the disorder can influence the cognitive development of those children. Children with acquired hydrocephalus might have normally developing cognitive functions up to the onset of their disorder and then have lost these functions, while children with congenital hydrocephalus might not even develop those functions at all (Iddon et al., 2004). Since hydrocephalus can result in secondary brain injuries, which can result in compression of the white and grey matter causing damage to cortical neurons (Del Bigio, 1993), concomitant cognitive and behavioral limitations can appear. Due to the differences in symptoms that can be caused by the two different onsets of hydrocephalus, we conducted the additional analysis, which excluded the children with acquired hydrocephalus and performed the statistical analysis using only those children with congenital hydrocephalus. Despite this exclusion, the differences in the reaction time in the mental rotation task still existed.

To explain the difference in mental rotation ability found in this study between SBHC children and HC children, one should consider other causal aspects in addition to the cognitive states of these children. The relationship between mental rotation and motor components has been a focus of investigation and this connection was thought to be a possible explanation for the results of this study. For example, Jansen-Osmann et al. (2008) examined the influence of mobility on spatial abilities in children with spina bifida. They found a correlation between the age of walking and performance in visuospatial memory and orientation in a maze. Children who learned to walk later in life performed worse than those who learned to walk earlier. Additionally, Stanton, Wilson, and Foreman (2002) showed that children with restricted mobility in early childhood perform worse in a simulated maze task than children with normal mobility. These studies suggest that free movement in early childhood enables children to explore spatial movement and develop spatial experiences, which have permanent influence on spatial behavior in later life. Further evidence for the relationship between locomotion and cognition is given by the study of Rendeli et al. (2002). They showed that children that can walk (with or without aids) exhibit significantly better scores in performance IQ than children that could not walk. This result indicates that some specific components in cognition, such as those that are linked to spatial organization, motor abilities, and specific locomotive skills, play a more relevant role in intelligence than one might assume. Additional evidence can be provided by studies that have investigated the influence of motor training on mental rotation performance in adults, healthy children, and children with spina bifida. The studies from Jansen et al. (2009), Jansen, Lange et al. (2011), and Lehmann and Jansen (2012) showed the beneficial effects of juggling training on mental rotation ability. More support for the suggested connection between motor abilities and cognition are given by the impaired mental rotation abilities in overweight children (who are assumed to be less active than normal weight children) (Jansen, Schmelter et al., 2011) and the superior mental rotation abilities demonstrated by preschool children with advanced motor skills (Jansen & Heil, 2010). To explain the trends found in these studies, it has been suggested that mental rotation processes are directly connected to motor processes (Funk et al., 2005). In this study they used pictures of hands as stimuli and participants were asked to decide whether the shown hand was a right or a left hand. Reaction times increased when the position of the shown hand was more difficult to transfer to the position of the participant´s own hand.

Considering these different approaches for examining the relationship between motor development and cognition, especially spatial cognition, one might assume that this relationship may account for the results of the current study as well. Children with spina bifida and hydrocephalus often have more severe motor ability deficits when compared to children with hydrocephalus only. The motor deficits in early childhood in children with spina bifida might account for their spatial deficits concerning the mental rotation ability. However, since none of these motor abilities have been measured with a standardized testing procedure, this relationship cannot completely be defined and therefore another explanation might account for the differences found between children with SBHC and children with HC.

Given that the impaired mental rotation ability in children with spina bifida has already been proven compared to healthy children (Wiedenbauer & Jansen-Osmann, 2007), no control group with healthy children was part of the study. Further research should include such a control group to be able to differentiate whether the children with HC are impaired in contrast to healthy children or if they have similar mental rotation ability. To clarify whether the differences between SBHC and HC in mental rotation are attributed to the varied motor development patterns in each disease over time, more detailed research is needed. Therefore, in future research physical activity and motor behavior have to be assessed with standardized measurements. Then, these should be compared to the performance in spatial abilities and mental rotation respectively. Furthermore, the localization of the lesion level should be considered in mental rotation. According to Fletcher et al. (2005), a higher lesion level is associated with poorer performance in neurobehavioral outcomes. Future research should include those variables in their analysis of cognitive measurement to determine the exact influence on spatial abilities. Additionally, future research has to consider the appropriateness of using the ZVT as a covariate in the investigation of children with neurological disorders. We have chosen the ZVT because it measures cognitive processing speed, but it correlates with different IQ measurements (Vernon, 1983). Dennis et al. (2009) suggested that using IQ as a covariate in children who have neurodevelopmental disorders is inappropriate because it does not meet the requirements of a covariate and influence the interpretation of cognitive processes. Furthermore, Dennis et al. (2009) recommended the inclusion of discriminate variables that are different from the dependent variable and therefore are more appropriate than IQ as a covariate. Consequently, further investigations of children with spina bifida should not include IQ as a covariate, but rather should focus on more appropriate discriminate variables, for example, top-down and bottom-up control (Dennis et al., 2005a).

In summary, children with both hydrocephalus and spina bifida show reduced mental rotation abilities compared to children with hydrocephalus only. It seems that this impairment might be connected with the motor abilities in these children. However, the exact relationship between mental rotation and motor abilities remains unclear. Future research should focus on this possible connection and whether a definitive relationship exists between specific motor abilities and mental rotation, or if this relationship is a more general one. Additionally, it should be considered whether the differences in mental rotation ability in this study are reproducible in other disease groups, or whether they are specific to neurological disorders, which often come along with secondary brain alterations. Eventually, the age of the participants should also be considered as an important variable. Does this relationship between motor ability and mental rotation occur in different age groups or is it specific only to the early stages of development?

The study shed light on the question whether the constrained motor abilities or the impaired cognitive skills are responsible for the impaired mental rotation performance in children with spina bifida and hydrocephalus. However, the exact underlying processes still remain unclear.

Before considering the underlying processes in the third experiment, it is the main focus of the second study to investigate if the impaired mental rotation ability is trainable. Due to the possible connection of mental rotation ability performance and motor abilities in children with spina bifida and hydrocephalus, the idea of the improvement of mental rotation performance through motor training is considered. If these processes are connected and are mutually dependent, the training of one of these processes should possibly have an effect on the other process. As a specific kind of motor training, namely juggling training, has already proven to be related to improvements in mental rotation performance, this kind of training is used in children with spina bifida as well. Thereby, the influence on mental rotation performance is investigated.

5. Experiment 2[1]

The influence of motor training on mental rotation performance in children with spina bifida was investigated in Experiment 1. It was assumed that juggling training, which has already been proven to improve mental rotation performance in healthy children and adults (Jansen et al., 2009; Jansen, Lange et al., 2011), is also considered suitable to improve mental rotation performance in children with spina bifida. To assess the trainings effect two groups of children, an experimental group and a control group, were investigated. It was anticipated that children with spina bifida who receive juggling training improve in mental rotation performance considerably more than children who do not receive training. This should be detectable in a decrease in reaction time from pre-test to post-test as well as an increase in mental rotation speed during the enquiry period. Additionally, the long term effects of such training were addressed in this experiment, assuming that improvement is still detectable after 6 months.

5.1 Method

5.1.1 Sample

Nineteen children with spina bifida (15 girls and four boys) aged between 8 and 12 (M = 9.74, SD = 1.45) years old took part in the study. Children were recruited by means of advertisement in local newspapers and in the journal of the *German Society of Spina bifida and Hydrocephalus* and with the cooperation of social pediatric centers in Bavaria, Baden-Württemberg, and North Rhine-Westphalia. Prior to testing, all parents gave their written consent for their children´s participation. The ethical review committee was informed.

The children were divided into two parallelized groups according to their age, gender, and their cognitive processing speed, measured with the Connecting Number Test (Oswald, & Roth, 1987), which could be transferred into IQ-values. Consequently, the two groups, experimental group (EG) and control group (CG), did not differ in their age (EG, M = 9.8, SE = 1.6; CG, M = 9.7, SE = 1.4; F (1,18) = .038, *n.s*), or in their

[1] The results presented in this chapter were published in advance in: Lehmann, J., & Jansen, P. (2012). The influence of juggling on mental rotation performance in children with spina bifida. *Brain and Cognition, 80*, 223-229.

IQ (EG, *M* = 78.9, *SE* = 11.1; CG, *M* = 78.3, *SE* = 8.0; *F* (1,18) = .016, *n.s.*). Gender was balanced between the groups. None of the children were able to juggle before participating in this study. All children received monetary compensation and juggling scarves and balls as gifts for their participation.

5.1.2 Breadboard

ZVT:

The Connection Number Test (ZVT; Oswald & Roth, 1987) measures cognitive speed. The numbers 1 - 90 are presented on four sheets with an irregular sequence in a matrix of nine rows and 10 columns. The participants are advised to connect the numbers in the ascending order as fast as possible with a pen. For each participant the time that was needed to connect all 90 numbers was measured. The time of all four sheets is then added and divided by four. The results can be converted into IQ estimations. The correlation between the ZVT and the standard IQ test is about r = .60 - .80 (Vernon, 1993). Internal consistency and 6-month test-retest reliability is about 0.90-0.95. The test was assessed once for each participant at the beginning of the time period.

Chronometric mental rotation test

All participants were assessed with a chronometric mental rotation test at the beginning and the end of an eight-week-time period. Each child was tested individually in familiar surroundings in front of a laptop with a 17`` monitor. The experimental stimuli consisted of 18 perspective line drawings of three dimensional cube figures similar to the ones used by Shepard and Metzler (1971) and Jansen-Osmann and Heil (2007a) (compare Figure 7).

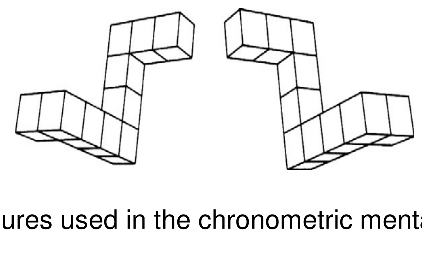

Figure 7: Example of the cube figures used in the chronometric mental rotation test.

The maximum size of each stimulus on the display was 7 cm x 7 cm and the distance between the stimuli was 14 cm. The children were allowed to choose their most comfortable viewing distance. Two stimuli were presented at the same time on the screen. The right stimulus was either identical to the left one or mirror-reversed. The angular disparity between the two stimuli was 0°, 90°, or 180° in a clockwise or counter-clockwise direction.

The children had to decide as quickly and accurately as possible whether the two stimuli were the same or mirror-reversed. To respond they had to press either the left button of the mouse (for the same) or the right button (for mirror-reversed). The two response buttons were marked with a green (left) and a red (right) point to clarify the options. Each trial began with a 500 ms blank background then the pair of stimuli appeared and remained on the screen until the participant responded. Based on the studies of Jansen, Titze et al. (2009) and Jansen, Lange et al. (2011) all participants received feedback in form of a "+" for a correct answer and a "-" for an incorrect answer. The feedback was presented for 500 ms on the screen. The next trial began after 1500 ms. Every combination of objects (18 cube figures), type of response (same/mirror-reversed), and angular disparity (0°, 90°, and 180°) was presented three times, resulting in a total number of 324 trials. To familiarize the children with the respective task a block of 54 unrecorded practice trials was performed at the beginning of the tasks. Afterwards, the block of 324 trials followed with breaks after every 27th trial. The reaction time and the error rates were measured and the same tasks and stimuli were used in the pre- and post-test. Both tests were separated by an interval of 8 weeks.

Mental rotation speed

According to Shepard and Cooper (1982) and Heil and Rolke (2002) several processing stages occur during mental rotation: perceptual processing, identification and discrimination of stimuli and identification of its orientation, mental rotation, judgment of parity, response selection, and execution. To investigate the influence of training on mental rotation itself, the mental rotation process needs to be excluded from the other processes. This can be done by analyzing the data with the help of regression lines between angular disparities and reaction times. The speed of the mental rotation process itself is indicated by the slope of the regression line. Therefore this analysis was conducted with the data of the participants.

5.1.3 Juggling training

During the 8 week period the children of the experimental group received juggling training once a week for 1 h. The training was comprised of the juggling of scarves, because they are slower and more convenient for children with myelomeningocele, rather than the juggling of balls. Every child was taught according to his or her individual abilities. This included that every child graduated to the next level of difficulty (more scarves or balls) only when they could juggle consecutively for at least 30 throws. At every session the numbers of successful throws were recorded. A throw was only counted as successful when the current juggling material was thrown and caught without interruption. A cascade with three scarves, in which each scarf is thrown and caught once, is counted as three throws. The data recorded included the throwing of one, two, or three juggling scarves from one hand to the other hand in the early training sessions and in the later training sessions the throwing of one or two juggling balls.

Children of the control group received no training and were requested to not learn juggling during the 8 week time period. After the study the juggling program was made available to all children of the control group.

5.1.4 Design and statistical analysis

For the analysis of the data the system SPSS 18.0 was used. Only correct answers were considered and the analysis was restricted to “same” responses because angular disparity is not unequivocally defined for “different” responses (Jolicoeur, Regehr, Smith, & Smith, 1985). Before the analyses the reaction times (RTs) were trimmed for outliners. The RTs more than two standard deviations above or below the mean per condition and per participant were excluded. For the experimental group this resulted in an exclusion of 2.3% of the pretest data and 2.5% of the posttest data; for the control group 2.2% of the pretest data and 2.2% of the posttest data was excluded. To investigate whether feedback has an influence on mental rotation performance we compared the error rates in the 12 different experimental blocks. Since the error rate did not differ between the several blocks in the pretest (F (11,198) = 1.52, *n.s.*, η^2 = .078) (F was averaged for the children in the intervention and control group), it was assumed that feedback did not have an influence on mental rotation performance.

One analysis of variance for the dependent variable difference-score in reaction time was calculated with the between-subject factor “group” (EG, CG) and the within-subject factor “angular disparity” (0°, 90°, and 180°). Difference score was considered to be effective since Souvignier (2000) and Rogosa, Brandt, and

Zimowski (1982) have considered this as valid measurement for the detection of changes in a pre-post-design. Despite previous assumptions that this is an invalid measurement they found that this is not true when considering the actual changes in individuals. Another analysis of variance for the dependent variable “error rate” was calculated with the between-subject factor “group” (EG, CG) and the within-subject factor “angular disparity” (0°, 90°, and 180°). Furthermore, the data was analyzed with respect to the motor abilities of the children independent of group: a univariate variance analysis with “difference score” as the dependent variable, the between-subject factor “motor abilities” (walking vs. wheelchair), and the within factor “angular disparity” (0°, 90°, and 180°) was conducted.

One analysis of variance was calculated with the dependent variable “mental rotation speed”, the between-subject factor “group” (EG, and CG), and the within-subject factor “angular disparity” (0°, 90°, and 180°) (compare Wiedenbauer, Schmid, & Jansen-Osmann, 2007). Mental rotation speed was calculated - separately for each participant - as the inverse of the slope of the regression line, relating RT and angular disparity, expressed as degree per second. Furthermore, the juggling performance was registered. All sets of data were tested for normal distribution.

5.2 Results

In addition to general information, the medical condition and infantile motor development were assessed by a questionnaire. All children had myelomeningocele and, apart from one child, all suffered from a shunted hydrocephalus. The localization of the lesion was lumbal in 15 children, thoracic and sacral in two children respectively. None of the children suffered from epilepsy, uncontrolled seizure disorder, perception disorder, or behavioral occurrences. Thirteen of the children learned to walk with or without assistance (6 in the intervention group, 7 in the control group). The other six children are not able to walk and sit in a wheelchair (4 in the intervention group, 2 in the control group). All children had normal or corrected to normal vision.

5.2.1 Improvement of juggling

All children in the experimental group showed an improvement in their juggling performance as a result of training. Table 3 shows the number of successful throws for each participant in the experimental group at the beginning and the end of the juggling training. More than 30 consecutive throws were considered as confident juggling (compare table 2). Although individual performance varied at the end of the training, all children of the experimental group except one were able to juggle reliably with at least two scarves.

Table 2: Improvement of juggling from pre- to post-test in the experimental group.

	Pretest				Posttest			
Participant	2 scarves	3 scarves	1 ball	2 balls	2 scarves	3 scarves	1 ball	2 balls
1	-	-	-	-	>30	>30	20	4
2	-	-	-	-	6	3	-	-
3	20	-	-	-	>30	5	5	-
4	20	-	-	-	>30	3	2	-
5	2	-	-	-	>30	11	>30	6
6	-	-	-	-	>30	5	3	-
7	-	-	-	-	>30	9	>30	5
8	-	-	-	-	>30	3	4	-
9	20	-	30	-	>30	6	>30	4
10	>30	-	30	-	>30	>30	>30	16

5.2.2 Reaction time

There was no main effect for the factor “angular disparity”, F (2,34) = 1.475, *n.s.*, η^2 = .080, but a significant main effect for the factor “group” F (1,17) = 6.102, p < .05, η^2 = .264, and a significant interaction between “angular disparity” and “group”, (F (2,34) = 4.751, p < .05, η^2 = .218. Children in the experimental group showed a decreased reaction time at all angular disparities (“0°”: M = -687.51 ms, SE = 208.47 ms; “90°”: M = -2014.75 ms, SE = 828.17 ms; “180°”: M = -1750.37 ms, SE = 584.46 ms). In contrast, the control group showed no such decrease in the reaction time (“0°”: M = -176.98 ms, SE = 114.41 ms; “90°”: M = 84.07 ms, SE = 640.29 ms; “180°”: M = 892.07 ms, SE = 707.88 ms). The before mentioned interaction is due to the fact that the difference between EG and CG is highest for 180° (*d* = 1.32) condition compared to the 0° (*d* = 1.08) and 90° (*d* = 0.91) condition (compare Figure 8).

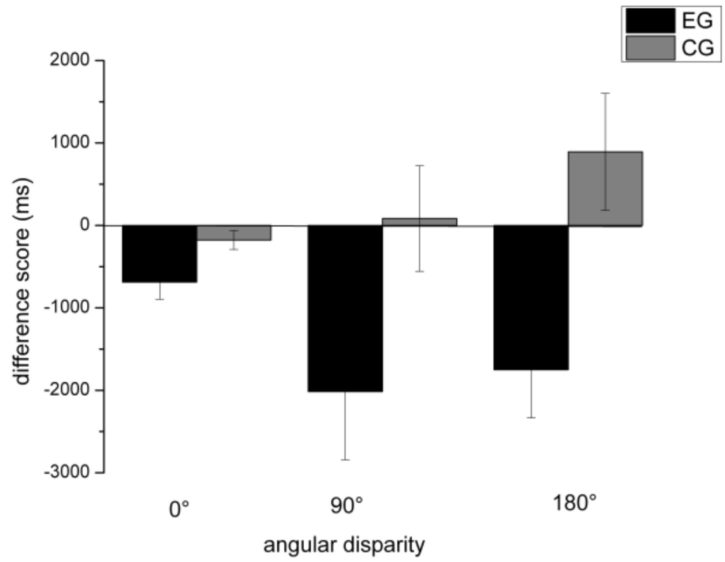

Fig. 8: Difference between the reaction times in the chronometrical mental rotation tasks from post- to pre-test. A more negative score indicates a lager reaction time gain. The results are presented separately for each group and angular disparity. Error bars indicate standard errors.

Concerning the effect of motor ability, there was no main effect for the factors “angular disparity”, F (2,34) = 1.04, *n.s.*, η^2 = .058, or “motor ability”, F (1,17) = .68, *n.s.*, η^2 = .004, and no significant interaction between “angular disparity” and “motor ability”, F (2,34) = .51, *n.s.*, η^2 = .003.

Interestingly, reaction time did not differ between 90° and 180° averaged over both groups of children (pretest: F (1,18) = 3.830, *n.s.*, η^2 = .175; posttest: F (1,18) = 1.492, *n.s.*, η^2 = .077).

5.2.3 Error rate

The repeated-measures ANOVA assessing the error rate discovered a significant main effect for the factor “group”, F (1,17) = 6.085, $p < .05$, η^2 = .264. Children in the experimental group reduced their errors (*M* = 6.06, *SE* = 1.80), whereas the children of the control group increased their errors (*M* = -1.26, *SE* 2.40). There was neither a significant effect of “angular disparity”, F (2,34) = .233, *n.s.*, η^2 = .014, nor for the interaction between both factors, F (2,34) = 1.168, *n.s.*, η^2 = .064.

5.2.4 Mental rotation speed

The analysis of mental rotation speed revealed a significant interaction between "time" and "group", $F\,(1,17) = 8.62$, $p < .05$, $\eta^2 = .336$. Children from the experimental group increased their mental rotation speed (pre: M = 64.41°/s, SE = 10.45; post: M = 91.28°/s, SE = 12.41). The control group showed a decrease in mental rotation speed (pre: M = 105.47°/s, SE = 18.80; post: M = 63.90°/s, SE = 8.37). (See Fig. 9)

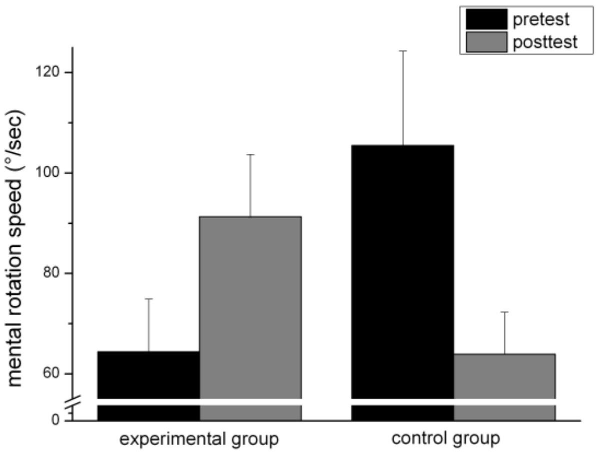

Fig. 9: Differences between pre- and post-test in mental rotation. A higher score indicates a faster mental rotation speed. The results are presented for each group and test time. Error bars indicate the standard error.

5.2.5 Additional results for the experimental group

Based on our results we chose to investigate whether the cognitive improvement was a lasting effect in our EG. Due to the missing progress for the control group in the mental rotation ability and the amount of time needed for assessing all children in the different parts of Germany, a 6-month follow up was only performed for the experimental group. Six months after the post-test every participant solved the chronometric mental rotation test again. We conducted a univariate analysis of variance with the dependent variable "reaction time", the within subject factor "angular disparity" (0°, 90°, and 180°), and the between subject factor "time" (pretest, follow up). The pre-test and follow up were chosen because pre-test and post-test data were already considered in the first analysis.

The factor "angular disparity" and "time" were explored with an analysis of variance. A significant main effect for "angular disparity", $F\,(2,18) = 66.15$, $p < .01$, $\eta^2 = .880$, and "time", $F\,(1,9) = 13.45$, $p < .01$, $\eta^2 = .599$, was found. Additionally, an interaction between both factors, F (2,18) = 4.584, $p < .05$, $\eta^2 = .337$, was shown. For the 0° condition the reaction time was lower in the follow up test (M = 1815.40, SE = 308.25) compared to the pre-test (M = 2671.96, SE = 489.49), F (1,9) = 12.52, $p < .01$, $\eta^2 = .582$, this was also found for the 90° condition, F (1,9) = 8.769, $p < .05$, $\eta^2 = .494$ (follow up: M = 3696.85, SE = 316.71; pretest: M = 6244.32, SE = 1003.45), and the 180° condition, F (1,9) = 16.72, $p < .01$, $\eta^2 = .650$ (follow up: M = 4112.75, SE = 604.62; M = 6007.49, SE = 769.90). Interestingly, in all three conditions (pre-test, post-test, and follow up) the experimental group´s reaction times did not differ between 90° and 180° (pre-test: F (1,9) = .602, *n.s.*, $\eta^2 = .063$; post-test: F (1,9) = .025, *n.s.*, $\eta^2 = .003$; follow up: F (1,9) = 1.221, *n.s.*, $\eta^2 = .119$).

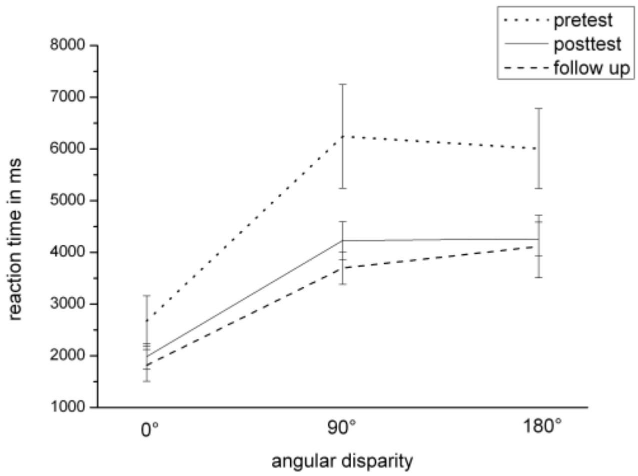

Fig. 10: Mean reaction times for the three test points across the three different angular disparities in the experimental group.

In Figure 10 we present the data from the pre-test, post-test and follow up test for the EG. Reaction time decreased from pre-test to post-test and to the follow up test; decrease for 0° (pre-posttest: d = 0.51; pretest-follow up: d = 0.66), 90° (pre-posttest: d = 0.85; pretest-follow up: d = 1.14), and 180° (pre-posttest: d = 0.94; pretest-follow up: d = 0.87) (compare Fig. 10).

5.3 Discussion

Due to the fact that the reaction time in the chronometric mental rotation test was influenced by the training, resulting in faster reaction time for the experimental group, it was shown that a beneficial influence of juggling on mental rotation performance also exists for children with spina bifida. This was proven for all angular disparities, although it is thought that in the 0° condition no mental rotation is needed. This study adds to the data of earlier reports about the influence of juggling on mental rotation performance in adults and school-aged children (Jansen, Lange et al., 2011; Jansen, Titze et al., 2009). Furthermore, the difference score gains in the conditions "90°" and "180°" produced in this study are similar to the results found in the juggling studies with adults and children mentioned above. In both conditions the reaction time gain was similar. The linear increase in reaction time in relation to increasing angular disparity (Shepard & Metzler, 1971) is a typical function observed in mental rotation tasks, but not in studies which describe the reaction time gain from pre- to post-test. Astonishingly, our data revealed no significant increase in the reaction times between 90° and 180°. This is in line with previous findings of Jansen-Osmann and Heil (2007a) who also did not find the linear increase in reaction time between 90° and 180° for cube figures. Additionally, the non linear increase between these two angular disparities has also been found in visuomotor mental rotation (Neely & Heath, 2009, 2010), who explained this differences with the use of an vector inversion strategy in the 180° condition which is cognitive less demanding and results in faster reaction times. This phenomenon might be explained by the specific design used in each experiment. We used only three orthogonally angular disparities (0°, 90°, and 180°) which might have led to these findings. Beyond this explanation one could assume that in 180° condition a different solution strategy (flipping the object) was used compared to the 90° condition (mental rotation). The use of different strategies might account for the non linear increase between these angular disparities.

Wiedenbauer and Jansen-Osmann (2007) have already presented the positive effect of manual rotation training on mental rotation ability in children with spina bifida. The present study confirms and enlarges these findings. While Wiedenbauer and Jansen-Osmann (2007) used two-dimensional drawings as stimuli for their study, this study confirmed the mental rotation improvement in children with spina bifida when using three-dimensional drawings. In comparison to the study of Wiedenbauer and Jansen-Osmann, an additional change was made regarding the intensity of training that was offered to the participants. Whereas the children in Wiedenbauer`s and Jansen-Osmann`s study had a one training session of 24 min, the training conducted in this study lasted 1 h per week for an 8-week-time period. Furthermore, the juggling training offered in this study is a more familiar, respectively more everyday-life based training, than the manual training and therefore more suitable to be integrated in the daily living of the children.

It has already been shown that children with spina bifida demonstrate decreased mental rotation ability and spatial abilities compared to healthy children (Wiedenbauer & Jansen-Osmann, 2006). This study shows that these children benefit from training with regard to these abilities. Our results are in line with other studies that highlight the benefit of training for spatial abilities, especially for those participants that initially show poorer mental rotation abilities (Rizzo et al. 2001). We found no differences between children who learned to walk and children who were restricted to a wheelchair regarding their mental rotation ability. This could mean that either children with spina bifida benefit from juggling training regardless of their motor abilities or that other motor abilities besides locomotion (walking vs. wheelchair) are important for the performance in spatial tasks. Since this research question was not part of this investigation, this aspect should be looked into in more detail in future studies. Additionally, it was shown that the improvement of the mental rotation ability outlasted the time in which training was offered and lasts at least as long as 6 months after the training. However, one has to consider that some of the benefit might result from learning.

Because we could show that the participating children indeed performed a mental rotation, which is proven by the increasing reaction times with increasing angular disparity (i.e. Shepard & Metzler, 1971), we also analyzed the reaction times further with regard to the mental rotation speed. The children in the experimental group showed an improvement in their speed from pre- (64.41°/s) to post-test (91.28°/s), children of the control group showed a decrease in the speed from pre- (105.47°/s) to post-test (63.90°/s). This indicates that children with spina bifida improve their mental rotation speed due to juggling training. When considering the different stages of mental rotation mentioned by Shepard and Cooper (1982) the findings of this study indicate that juggling has a direct effect on the stage in the mental rotation process which requires the rotation. Since it was shown that the slope of the regression differed between the two groups from pre- to post-test, the difference can be attributed to the “rotation of the objects” stage. This is in line with the results of Wiedenbauer and Jansen-Osmann (2007), who also found an improvement in mental rotation itself after training. Because the gain in mental rotation speed after the juggling training was also visible in the 0° condition, juggling seems not only to improve the rotation itself but also the stages in the rotation process where encoding is required.

Changes in neurophysiologic processes due to juggling were already shown by Draganski et al. (2004) and Scholz, Klein, Behrens, and Johansen-Berg (2009). Draganski et al. (2004) revealed that a three month juggling training induces an increase in brain plasticity in exactly that area, namely the intraparietal sulcus, which is involved in mental rotation (Jordan et al., 2001). Draganski et al. (2004) found that the experimental group had a significant gain in gray matter in the mid-temporal area and the intraparietal sulcus. Therefore, they concluded that juggling, which involves the perception and the spatial anticipation of objects, has an impact on the structural plasticity in the visual areas. These neuroscientific findings were expanded by the findings of Scholz et al. (2009) who also found changes in gray matter after juggling training, but could additionally show that these changes also occur in white matter. With diffusion tensor imaging they found significant increases in the white matter in the posterior intraparietal sulcus of the experimental group. These findings were independent from the training progress. These neurophysiological findings can further be supported by the study from Eisenegger, Herwig, and Jäncke (2007). They found an activation of the primary motor cortex corresponding to the hands while performing a mental rotation task, suggesting that this brain area is generally involved in the processes of a mental rotation task. Since juggling is a motor behavior using the hands, it is assumed that the primary motor cortex is activated during this task (Scholz et al., 2009). According to Eisenegger et al. (2007) the primary motor cortex is involved in mental rotation and thus juggling seems to have a direct influence on mental rotation.

Based on the changes in neurophysiologic processes one might also assume that the improvement in mental rotation might be due to improvement in the action-based visual perception of children with spina bifida. Dennis et al. (2002) showed that children with spina bifida have an impaired performance in action-based tasks, which includes mental rotation. According to Dennis et al. (2002), action-based tasks require representations of multiple stable states and therefore are coupled to movement. This relationship might be the basis on which the improvement in mental rotation through motor training is explained. Because of the practice and the improvement in juggling, the coordination of multiple stable states might be trained with this task and through that result in a better performance in the mental rotation test at the end of the training. This can be explained from a more behavioral point of view by the idea that these two abilities (juggling and mental rotation) are connected through their underlying features. Both abilities require cyclic activities and temporal and spatial constraints (Jansen, Titze et al., 2009). During throwing and catching in juggling the hands move along trajectories that are more or less elliptical (Post, Daffertshofer, & Beek, 2000); during mental rotation cyclic trajectory movements around three axes are needed to bring one object into the position of the standard object. Whereas mental rotation is thought of as a covert manual rotation (Wohlschläger & Wohlschläger, 1998), juggling is considered to be similar to a spatial clock (Post et al., 2000).

Given that the improvement in mental rotation performance was already proven to be specific to juggling training, no training was used in the control group. Former studies have shown a beneficial effect of juggling training compared to non-training (Jansen, Titze et al., 2009) and compared to stretching training (Jansen, Lange et al., 2011). Because the "juggling effect" did not differ due to the control group (no training vs. other motor training) it was decided to use a control group without training due to the high economic effort and difficulties to conduct this study. However, future studies should include a training control group to rule out that the improvement is due to the additional attention and enrollment of activity that the experimental group received. Additionally, one might argue about the stimuli used were inappropriate because of their three-dimensionality, but since the children showed the linear increase in reaction time with increasing angular disparity, it can be assumed that the children were able to solve this task using mental rotation. These stimuli were selected in order to compare this study to earlier studies regarding the influence of juggling on mental rotation performance (Jansen, Lange et al., 2011; Jansen, Titze et al., 2009). Furthermore, the follow-up did offer an interesting result, but the limitation created by the missing control group must be considered carefully. In future studies the influence of training on different stimulus material might be an interesting topic as well as the use of other objects in the posttest to investigate transfer effects in more detail.

Children with spina bifida benefit from juggling training regarding their mental rotation ability. They demonstrated a decrease in reaction time due to the training compared to a control group. This effect was still observable in the follow-up test. Therefore, this study shows that the improvement of the mental rotation ability through juggling is not only present for healthy children and adults, but for children with spina bifida as well. Furthermore, the study suggests a possible therapy that could be considered for children with spina bifida. Future research must investigate whether the results are also found for different age groups of children with spina bifida and if further cognitive abilities are influenced by motor training in these children. Additionally, it should be investigated whether people with other neurological disorders also benefit from training with regard to their mental rotation ability.

What were not tested in children with spina bifida next to their impaired motor abilities are their other possible impaired cognitive abilities as for example working memory or executive functions. The exact underlying processes still remain unclear. Consequently, the third study addresses this topic more specifically. The relationship between mental rotation, motor abilities, and working memory performance is investigated to contribute to the question, whether indeed motor abilities are closer connected to mental rotation performance as cognitive skills.

6. Experiment 3

Experiment 3 investigated the relationship between mental rotation, motor abilities, and working memory. Thereby it should be clarified whether motor abilities or cognitive abilities influence mental rotation performance. To assess this relationship, a correlation analysis as well as regression analysis was conducted to measure the influence of the different factors on mental rotation performance. Due to previous studies it was assumed that motor abilities are connected closer to mental rotation performance than working memory processes. Therefore, it was supposed that the performance on motor tests could provide indications on the level of mental rotation abilities, whereas the performance on working memory tasks could not predict mental rotation performance.

6.1 Method

6.1.1 Sample

A total of sixty-five children (32 boys and 33 girls) aged between 3 to 6 years old participated in this study. The mean age of the girls was 5.13 (± 0.89) years and the mean age of the boys was 4.86 (± 1.04) years. All participating children were recruited from a kindergarten in Kreuztal. Prior to testing, all parents gave their written consent for their child´s participation. The kindergarten received 500 Euro of gratification for their participation. This experiment was run according to the ethical principles of the American Psychological Association.

6.1.2 Breadboard

All children had to complete the Coloured Progressive Matrices test (Raven, Court, & Raven, 1976), the Picture Rotation test (Quaiser-Pohl, Rohe, & Amberger, 2010), the Block Tapping Test (Kaufmann et al., 2008), the Digit Span test (Petermann & Petermann, 2010), and the Movement ABC-2 (Petermann, 2009). Additionally, a questionnaire with general information had to be completed by the parents. No child had a documented history of a neurological disorder.

Measurements used to assess the mental rotation performance:

The mental rotation performance was measured with two different mental rotation tests. One test was a paper and pencil test, whereas the other one was a chronometric mental rotation test.

Picture Rotation Test:

The Picture Rotation Test (PRT; Quaiser-Pohl et al. 2010) is designed as a paper and pencil mental rotation test. The test consists of 2 practice items and 16 test items. In each item four pictures are presented. One of those is the standardized picture, illustrated on the left side, and the others are three repeated pictures on the right side rotated in relation to the standard in 45°, 90°, 135°, or 180°. Only one of the three pictures depicted for the purpose of comparison is identical to the standardized stimulus presented on the left side; the other two pictures are mirror-reversed images. Participants are advised to decide and mark which one out of the three rotated pictures is identical to the standard picture. No time limit is set for the test and the maximum score is 16 points. The split-half reliability is .74.

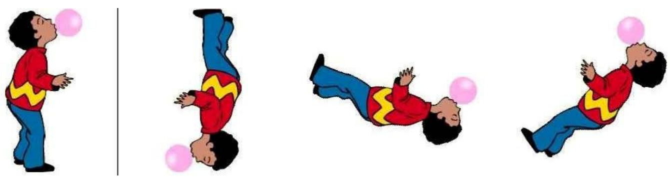

Figure 11: Example for an item of the Picture Rotation Test (Quaiser-Pohl et al., 2010).

Chronometric mental rotation test

The chronometric mental rotation test (CMRT) used twelve different animal pictures as stimuli (grizzly bear, elephant, donkey, dog, camel, crocodile, sheep, lion, pig, zebra, rhinoceros, and turtle; taken from Roisson & Pourtois, 2004).

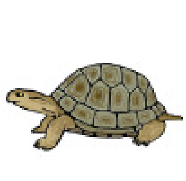

Figure 12: Item example for the stimuli used in the chronometric mental rotation test (Roisson & Pourtois, 2004)

The maximum size of each stimulus on the display was 5 cm x 5 cm and the distance between the stimuli was also 5 cm. The children were allowed to choose their most comfortable viewing distance. Two stimuli were presented on the screen at the same time. The right stimulus was either identical to the left one or mirror-reversed. The angular disparity between the two stimuli was 0°, 90°, 180°, or 270°. The experiments were run on a laptop with a 17`` monitor (see Hahn et al., 2010a, 2010b).

The children had to decide if the two stimuli were the same or mirror-reversed. Therefore, they had to press either the left button of the mouse (for "same") with their index finger or the right button (for "mirror-reversed") with their middle finger. The two response buttons were marked with a green (left) and a red (right) point to clarify the options. Children were told to respond as quickly and accurately as possible. The trials were presented in 4 blocks: blocks one and four were comprised of only upright stimuli and blocks two and three were comprised of rotated stimuli (90°, 180°, 270°). Each trial began with a one second blank background and a fixed cross in the middle of the screen. Afterwards, the two animals appeared and remained on the screen until the child gave the button response. All participants received feedback in form of "+" for the right answer and "-" for the incorrect answer. The feedback was presented on screen for 500 ms. The next trial then appeared after one second. Every six trials the children had the opportunity to take a break. In blocks one and four the combination of the 12 stimuli, the type of response (same/mirror-reversed), and direction of rotation (clockwise/counter-clockwise) resulted in 48 trials for each block. In blocks two and three the combination of the 12 stimuli, the type of response (same/mirror-reversed), the angular disparity (90°, 180°, 270°) and direction of rotation (clockwise/counter-clockwise) resulted in 72 trials per block. A total of 240 trials had to be solved with brakes after every 12th trial. Each block was preceded by 12 practice trials to familiarize the children with the respective task. The reaction time and the error rates were measured.

Measurements for intelligence and working memory:

The participants were tested with a non-verbal intelligence test and different working memory tests to assess all components of working memory.

Coloured Progressive Matrices:

The Coloured Progressive Matrices (CPM) Test is a language independent test designed to measure the child´s ability to form perceptual relationships and to reason by analogy. This test measures the Spearmen´s g. Thereby, the test consists of 36 items, which are arranged in three sets of 12 items each. Each item represents a specific pattern in which one piece is missing. Beneath each task six alternatives pieces are presented to complete the pattern. Whereas each piece contains the correct form, only one piece presents the correct pattern. The three different sets include different strategies for obtaining the missing piece. Within each set the items are roughly arranged in increasing order of difficulty. Retest reliability lies at .90, inner consistency amounts to .64-.82 (Becker, Schaller, & Schmidtke, 1980).

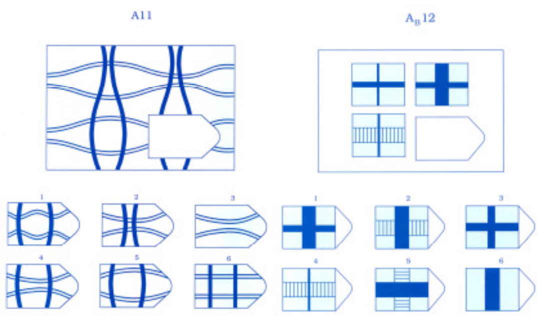

Figure 13: Two different examples for the Coloured Progressive Matrices Test (Raven et al., 1976).

Digit Span:

The Digit Span Test is a measurement that captures the performance on both slave systems of working memory. This test is part of the Hamburger-Wechsler-Intelligence-Test for children (HAWIK-IV; Petermann & Petermann, 2010). Whereas the phonological rehearsal processes are measured with the forward version of the digit span test, verbal working memory processes are assessed with the backward version. Participants are advised to repeat the numbers that are orally presented by the examiner, in either the same or the reverse order. Feedback is limited to the practice trials. The difficulty in both test versions is determined through the length of the list of numbers that could be recalled either forward or backward. In each level of difficulty two sequences are presented. When a sequence cannot be repeated successfully by the participant the test is finished. Maximum score for the task forward is 32 with a split-half reliability of .76, maximum score for the test backward is 16 with a split-half reliability of .78.

Corsi-Block-Tapping Test:

The Corsi-Block-Tapping Test (Kaufmann et al., 2008) is a measurement for different parts of working memory. Particularly, there are two variants of the test: the forward test measures the visuospatial sketchpad, whereas the backward test measures the central executive of working memory. The test itself is presented on a wooden panel (32 cm x 25 cm) on which nine wooden blocks (4,5 cm x 4,5 cm) are fixed in a specific order. The blocks are marked on one side with ascending numbers from one to nine, which are visible only to the examiner, whereas on the other side no such tags are presented. Using the index finger the examiner points a sequence of blocks to the participant, who has to repeat the sequence by tapping the blocks either in the same order (forward test) or in the reverse order (backward test). The numbers of blocks within a sequence determines the level of difficulty. When the participant is not able to recall all three attempts presented within a sequence the test is finished. The maximum score for each participant is determined by the length of the block that could be repeated at least two times successfully. The reliability of this test is between .81 and .89.

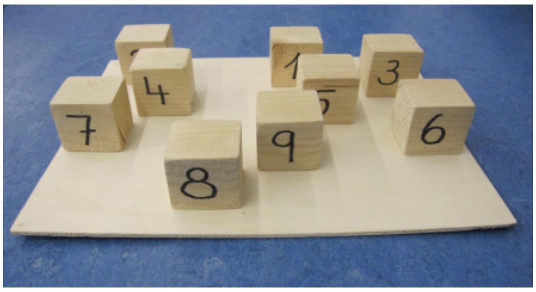

Figure 14: Self-created Corsi Block Tapping Task according to Kaufmann et al. (2008).

Motor skill measurement

The assessment of motor abilities in children was performed with a test that is appreciated in science regarding reliability and validity. Due to the huge amount of available measurements it was decided to choose the test presented here, which covers a variety of motor skills, as well as a total motor score.

Movement-ABC-2:

The development of motor skills in children can be evaluated with the Movement Assessment Battery for Children 2 (M-ABC-2; Petermann, 2009). This measurement was developed for children between 3.0 years and 16.11 years with task difficulties complementing the age group. Instructions were given according to the Movement ABC-2 manual. Each child has to solve eight motor tasks which are assigned to specific categories. These categories are: manual dexterity, ball skills, and static and dynamic balance. In accordance with the investigated age group, the tasks for children from 3.0 to 6.11 years of age were applied. For the measurement of manual dexterity the participants had to perform the task “insert coins”, “thread beads”, and “drawing trail”; the ball skills were assed with “throwing a sandbag”, and “catching a sandbag"; static and dynamic balance comprised the tasks "one leg stand", "walking with heels up", and "mat bouncing".

"Insert coins" persists of the task to thrust coins as fast as possible through a small slot into a box while holding this box with the other hand. Performance on left and right hand is measured in seconds. When performing "thread beads", the participant is advised to thread beads as quickly as possible. During this, one hand is holding the string, while the other hand is threading the beads. When the participant has to perform the "drawing trail", a predefined trace should be followed with a pencil with as few oversubscriptions as possible. The tasks to measure the ball skills of the participants are carried out on two pads that are fixed at a defined distance. The examiner is standing on one of the pads when throwing the sandbag. The participant is standing on the other pad and is advised to catch the sandbag. When the participant executes the "throwing a sandbag" task, he or she is standing on one of the pads and must throw the sandbag into a circle that is positioned at a defined distance on the other pad. To test the balance, the participant is advised on one leg for as long as possible. In these tasks the maximum standing time for both legs are measured. The participants are asked to walk on a fixed line with a defined length with heels up as exactly as possible. For the tasks "mat bounding" five mats are positioned against each other and on each mat the participant needs to jump once with both feed.

The evaluation of each task was performed according to the guidelines of the manual. The results are presented for each of the three categories and as a total motor score. The inter-rater-reliability for the M-ABC-2 is .95 and the retest-reliability is .95.

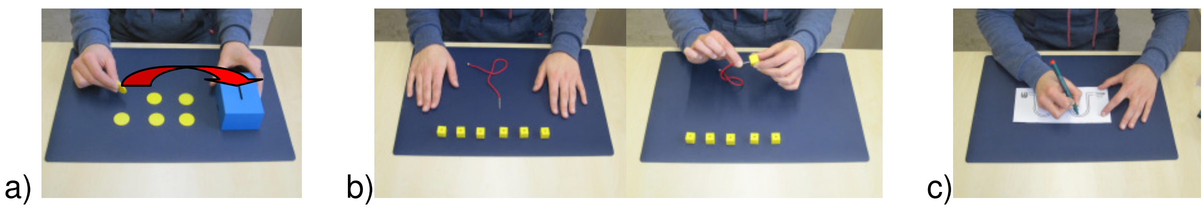

Figure 15: Examples of the manual dexterity tasks of the M-ABC-2 (Petermann, 2009). a) "insert coins"; b) "thread beads", and c) "drawing trail"

6.1.3 Test execution

Every child was tested individually on two different days over a period of two weeks. Each testing session lasted one hour. During the first session the chronometric mental rotation test, Corsi test, and the Digit span test were conducted to each child. The second session comprised the CPM, the Movement ABC-2, and the PRT. All of the tests were conducted in quiet spare rooms of the kindergarten. At the end of each session the child received small rewards, for example, an armlet. All tests were conducted by the same principal investigator.

6.1.4 Design and statistical analysis

For the analysis of the data the system SPSS 18.0 was used. Before analyzing the CMRT, data was trimmed for outliners. Reaction time data more than 2 standard deviations above or below the mean per participant and per condition were excluded. Only correct answers as well as "same" responses were analyzed. Reaction time and error rate were analyzed with factorial repeated-measures ANOVA with "angle of rotation" as within subject factor.

Subsequently, a multiple correlation analysis was conducted between the PRT, the M-ABC-2, and the working memory tasks. Due to multiple testing in the correlation analysis, the significance level was corrected by the Bonferroni method and $p \leq .007$ was considered significant. Regression analyses were carried out with the PRT as dependent variable. For further analysis the children were divided into in two age groups, 3-4-year-old children (28; 13 boys, 15 girls) and 5-6-year-old children (37; 20 boys, 17 girls). Two separate correlation analysis for both age groups between mental rotation and the other variables were calculated. Again, due to multiple testing in the correlation analysis, the significance level was corrected by the Bonferroni method and $p \leq .007$ was considered significant.

6.2 Results

Analysis of the data for the CMRT

Reaction time

Reaction time was assessed using a repeated-measures ANOVA and revealed, after correction with Greenhouse-Geisser, a significant effect for the factor "angular disparity", F (2.07,156) = 21.415, $p < .01$. The reaction time increased with the increasing angular disparity for all angles besides "270°": "0°" (M = 4358.44 ms, SE = 2085.55 ms), "90°" (M = 6292.03 ms, SE = 3413.04 ms), "180°" (M = 6970.85 ms, SE = 3798.50 ms). For the condition "270°" (M = 6089.06 ms, SE = 2903.20 ms) the reaction time was shorter than the one for 180°.

Contrasts revealed that the difference between the rotated conditions and the upright condition were significant ("90°": F (1,52) = 26.409, $p < .01$; "180°": F (1,52) = 31.808, $p < .01$; "270°": F(1,52) = 27.365, $p < .01$). Additionally, the calculated contrasts showed no significant difference between "90°" and "270°" (F (1,52) = .769, *n.s.*), whereas the differences between "90°" and "180°" (F (1,52) = 6.423, $p < .05$) and "180°" and "270°" (F (1,52) = 8.290, $p < .01$) were significant.

Error rate

The repeated-measures ANOVA discovered a significant effect for the factor "angular disparity", F (2.56,156) = 20.746, $p < .01$, after Greenhouse-Geisser correction. The error rates increased with angular disparity up to "180°" and then decreased at "270°" (with means of 18.4% (± 11.29) for "0°", 28.2% (± 17.17) for "90°", 35.1% (± 20.4) for "180°", and 26.4% (± 16.29) for "270°").

When looking at the contrasts for the error rate, similar results as for reaction times were detected. The contrasts identified significant differences between the three rotated conditions compared to the upright condition ("90°": F (1,52) = 27.004, $p < .01$; "180°": F (1,52) = 37.944, $p < .01$; "270°": F (1,52) = 19.560, $p < .01$). Furthermore, no significant differences were noticed between "90°" and "270°" (F (1,52) = 1.297, *n.s.*). In comparison, the differences between "90°" and "180°" (F (1,52) = 8.915, $p < .01$) and "180°" and "270°" (F (1,52) = 14.418, $p < .01$) were significant.

Although we found the typical linear angular disparity effect when looking at the complete data from the chronometric mental rotation test, the individual means of the children did not show the effect. This can be accounted for by the high standard deviation of the reaction times and error rates. For this reason we concentrated the correlation analysis only on the results observed with the PRT (compare Jansen & Heil, 2010).

6.2.1 Correlation analysis

Mental rotation performance compared to working memory and motor abilities

The relationship between the different measurements used was assessed with a correlation that was calculated between the picture mental rotation and the different tests for working memory and motor skills. The results for this analysis are shown in Table 3.

Table 3: Results of the correlation analysis of the PRT, the working memory and motor tests are presented. The significance level is adjusted according to Bonferronis to *p*<.000694.

	1	2	3	4	5	6	7	8	9
1: Digit recall Forward	-								
2: Digit recall Backward	.831*	-							
3: Corsi forward	.552*	.499*	-						
4: Corsi backward	.652*	.609*	.523*	-					
5: Manual Dexterity	.312	.312	.450*	.371	-				
6: Ball skills	.082	.155	.278	.289	.583*	-			
7: Balance	.412*	.412*	.443*	.365	.622*	.549*	-		
8: Total motor Score	.329	.346	.479*	.408	.853*	.824*	.846*	-	
9: PRT	.729*	.668*	.565*	.534*	.353	.229	.418*	.408	-

* $p < .000694$

A positive correlation was found between the picture mental rotation test and all four working memory tests (digit span fw: r = .729; digit span bw: r = .668; Corsi fw: r = .565; Corsi bw: r = .534) as well as between the picture mental rotation test and the balance test (r = .418). Furthermore, a correlation between balance and the working memory tests digit span forward (r = .412) and backward (r = .412), and Corsi forward (r = .443) was found.

A further conducted separate correlation analysis for the age groups revealed significant correlations between PRT and both digit span tests for the younger age group (3-4 years) (digit span fw: r = .568; digit span bw: r = .530), as well as between PRT and balance (r = .499), ball skills (r = .548), and the total motor score (r = .588). The correlation analysis for the older age group (5-6 years) revealed only a significant correlation between the PRT and the digit span forward (*r* = .561) and backward (*r* = .495).

Due to the fact that bi-variate correlations do not determine in which way variables affect each other, a stepwise multiple regression with the PRT performance as criterion and the following predictors was conducted: performance on the CPM, digit span forward and backward, Corsi forward and backward, manual dexterity, ball skills, balance, total motor score, age in months, and gender. The regression was tested for multicollinearity, but revealed none in the data.

6.2.2 Regression analysis

The multiple regression results revealed that 55.5% of the variance (R^2 = .569) is explained by the predictors digit span forward and Corsi forward, F (2,64) = 40.97, *MSE* = 529.686, $p < .001$ (see table 4.).

Table 4: Results of the final stepwise multiple regression model for the mental rotation performance based on the following predictors: gender, age in months, ball skills, manual dexterity, balance, total motor score, Corsi backward, Corsi forward, digit span forward and backward, CPM are depicted.

Predictor	ß	T	p
Digit span forward	.600	6.001	< .01
Corsi forward	.234	2.341	< .05
Gender	.070	.792	> .25
Age	.133	1.139	> .25
Ball skills	.125	1.452	> .05
Manual dexterity	.077	.816	> .25
Balance	.088	.926	> .25
Total motor score	.129	1.364	> .05
Corsi backward	.039	.336	> .25
Digit span backward	.173	1.151	> .25
CPM	.167	1.638	> .05

6.3 Discussion

The relationship between mental rotation ability, working memory, and motor ability was investigated in this study.

A high correlation of the two working memory tests and mental rotation task as well as the working memory tests, balance, and mental rotation was shown. The correlation between balance and the PRT is in line with the study of Jansen and Heil (2010), who found a correlation between PRT and coordination, and was reproduced and expanded in this study for children as young as 3 and 4 years of age. Children with higher scores in the PRT performed better on the balance tasks. This study goes beyond that of Jansen and Heil (2010), because it was found that, in addition to motor ability, working memory is an important component of the mental rotation processes. Interestingly, when separating the children in two age groups, the motor effect was prominent in the younger age group, but not in the older one. For sure, this has to be taken with caution, because the number of participants was quite low in each age group. However, at least it gives a hint that there might be a change in the importance of motor processes in mental rotation in childhood. This is in line with the study conducted by Frick et al. (2009), who showed the importance of motor processes only in younger children. However, the results are contradictory to the study of Krüger and Krist (2009a). They investigated mental rotation using pictures of body parts and found that mental rotation ability was correlated to motor abilities for 7-year-old children and adults. But not for children aged 5-6 years. Our study revealed also that working memory processes do play a role within the mental rotation paradigm as young as 3-4 years of age. This is a new result, which deserves further attention. Since the separation in two age groups is limited due to the low number of participants in each group, the focus of the discussion is dedicated to the overall analysis.

Until now, evidence for the relationship between mental rotation and working memory has already been found using psycho-physiological methods (Heil et al., 1998; Band & Miller, 1997) and imaging technology (Anguera et al., 2010; Jordan et al., 2001; Suchan et al., 2006). However, to our knowledge, this is one of the first studies to find this connection on a behavioral level. As our results show when analyzing the data for all children, the performance on the test for the visuospatial sketchpad (Corsi forward) and the phonological loop (digit recall forward) are related to mental rotation:

children who performed better in working memory tasks showed better results in the PRT. This helps to clarify the relationship between working memory and mental rotation.

This involvement of working memory in mental rotation is in agreement with the findings of Hyun and Luck (2007), who examined the visual working memory during a mental rotation task with the assumption that storage of an object is needed to perform a mental rotation task. Using letters as stimuli, they found an interaction between mental rotation performance and the object working memory, but no involvement of the spatial working memory. This result supports the hypothesis of Carpenter et al. (1999) that during mental rotation the dorsal and ventral streams are activated and that the ventral stream is involved with storage, while the dorsal stream is involved with mental rotation. This separation of the processes of the visuospatial sketchpad is in line with the suggestion of the results of Bruyer and Scailquin (1998). They suggested that there are two subsystems in the visuospatial sketchpad, namely one that passively stores visuospatial information and one that recapitulates visuospatial information. Furthermore, their results showed that the interference of the visuospatial sketchpad decreased with increasing task complexity. Their results indicate that the visuospatial sketchpad is involved in at least two substages of mental rotation: first the rotated image is stored and in a later step this image is compared to the standard image.

As the separation of the two slave systems is stated in literature (Baddeley, 1992, 2000; Bruyer & Scailquin, 1998), the present study indicates that the involvement of the phonological loop in the mental rotation process needs further attention, at least concerning preschool children.

According to Gathercole et al. (2004), the involvement of the phonological loop in the processes of mental rotation might be that the phonological loop recodes non-phonological inputs into phonological forms. This is done so that the information can be held in the phonological store and be easily recalled as needed. Since the mental rotation ability was assessed using pictures in this study, the children might have relied on the rehearsal processes of the phonological loop to solve the mental rotation task. This might explain the connection between the digit span forward test and the mental rotation. As this test measures the storage capacity of one slave system of working memory, it is assumed that during mental rotation the rotated object needs to be stored in order to compare it to the shown stimuli. Normally, the phonological loop and its rehearsal processes are used for storing familiar objects. The objects used in this study were considered familiar objects and this process becomes more important with age. In young children, the phonological loop is not fully developed. Therefore, it is possible that they rely more heavily on the processes of the visuospatial sketchpad (Gathercole et al., 2004). However, this theory is not supported by our study, since we did find a correlation between the phonological loop and mental rotation for children from 3-6 years old.

Further evidence for the involvement of the phonological loop in mental rotation abilities might be found in studies with dyslexic children. Dyslexia is a reading disability, the cause of which is still controversially discussed. It is still not clear whether it can be attributed to phonological deficits or if the problem lies elsewhere (Démonet, Taylor, & Chaix, 2004; Vidyasagar & Pammer, 2010). If the involvement of the phonological loop is important for mental rotation, as it is suggested in this study and in the study of Rüssler, Scholz, Jordan, and Quaiser-Pohl (2005), a study which demonstrates impaired mental rotation ability in children with dyslexia (irrespective of the stimulus material used), could help to further define the role of the phonological loop in mental rotation as well as the underlying cause of dyslexia.

To our knowledge, this is the first study which has investigated the relationship between working memory processes, motor ability, and mental rotation performance. Also, it is the first study that has shown that the connection between motor ability and mental rotation diminishes when working memory processes can be taken into account. Continued investigation into the relationship between mental rotation and working memory is needed to understand the underlying processes involved. Furthermore, the relationship between motor ability, working memory, and mental rotation might also be considered in executive function research. Since working memory is one aspect of the executive functions of cognitive abilities and has been linked to motor abilities on both a behavioral and a neuroanatomical level (Pangelinan et al., 2011), the executive functions may play an important role in the relationship between these different aspects. Wassenberg et al. (2005) already indicated a relationship between attention, executive functioning, and motor performance. Future research must investigate how all of these aspects influence mental rotation and cognition under special attention of age.

The presented results and discussion of both this experiment and the other two experiments are discussed in a wider context in the final concluding discussion. The presented results and discussion of this experiment as well as the results and discussion of the other two experiments are discussed in a broader understanding in the final discussion. Thereby, an extended point of view regarding the topic of mental rotation and the underlying processes is considered.

7. Concluding discussion

The final chapter of this PhD thesis deals with the summary and discussion of the results of the three experiments. At the beginning, the results of the first two experiments are discussed together against the background of the relevance of these results for children with impaired spatial abilities and the possible influence of these results on inter alia daily living and possible changes in therapeutic concepts. However, the focus is laid on the involved processes in mental rotation based on the results of the first two experiments as well as results of the third experiment. Thereby, the involvement of working memory processes in mental rotation as well as the scope of influence of training on this specific relationship and, for that matter, on the relationship between working memory, motor skills, and spatial skills is addressed.

7.1 Mental rotation in children with neurological disorder

In Experiment 1 and 2 the mental rotation performance in children with spina bifida and hydrocephalus and children with hydrocephalus only as well as the effects of training on this ability were investigated. It was presumed that the impaired mental rotation performance in children with spina bifida might rather be due to the impaired motor skills associated with spina bifida rather than the hydrocephalus. This could be confirmed in the first study. The second study showed the beneficial influence of motor training, in form of juggling training, on mental rotation performance in children with spina bifida.

To begin with the comparison of mental rotation performance of children with SBHC and children with HC, the focus is laid at first on reaction times. Already Wiedenbauer and Jansen-Osmann (2007) showed impaired spatial abilities in children with spina bifida and more precisely impaired mental rotation ability in those children. This was indicated by slower reaction times for the children with spina bifida compared to healthy children. With regard to the reaction times found in the first experiment, differences between SBHC and HC are detectable even when cognitive speed is included in the analysis as a covariate. Children with SBHC showed slower reaction times compared to children with HC. This was noticeable in all measured angular disparities. When comparing the mean of the reaction times between SBHC and HC, the ones for children with SBHC are apparently higher in all conditions compared to children with HC. Although it is critical to compare results across different experiments, the results of reaction times were looked into in another experiment. The means of reaction times of Wiedenbauer and Jansen-Osmann (2007) are due to different experimental design and are therefore not completely comparable to the ones in this work. However, the tendency of the means indicate that children with HC are more likely to perform similarly to healthy children regarding the reaction times and less likely to perform similar to children with SBHC. Therefore, the results of the experiment presented in this PhD indicate that children with HC differ from children with SBHC regarding their mental rotation performance. Consequently, the aspect of the etiology of hydrocephalus should be considered when investigating spatial abilities in children with hydrocephalus.

As mentioned in chapter 5.3, the results of the quasi-experiment employed in this thesis are contradictory to other studies, which did not find such distinctions between children with spina bifida and hydrocephalus and children with hydrocephalus only (inter alia Iddon et al., 2004; Lindquist et al., 2008, 2009). While Lindquist et al. (2008, 2009) used rather general measurements to assess inter alia memory and executive functions, the here presented study investigated only one specific aspect of spatial ability, and that is mental rotation. Therefore, one could draw the conclusion that while in general cognition, memory, or executive function no differences in performance are found between children with SBHC and children with HC only, these differences in performance are detectable when looking in specific aspects of spatial abilities - specifically mental rotation. Further research is needed to prove this rather general statement but for mental rotation ability evidences for different performances are found.

But where can these differences in mental rotation performance be attributed to? Several explanations are possible for these findings. It is assumed that in mental rotation visual encoding processes (for example Paschke, Jordan, Wüstenberg, Baudewig, & Müller, 2012), working memory processes (Hyun & Luck, 2007), as well as motor processes (compare Wohlschläger & Wohlschläger, 1998; Wexler et al., 1998; Zacks, 2008) are participating. Therefore, the different stages in mental rotation are considered more closely. Since mental rotation is composed of encoding processes, mental rotation processes, and decision making processes, these different processes need to be considered individually in supplying an explanation for possible differences in mental rotation.

First of all, encoding processes are comprised of the perceptual processing of the stimuli, the identification and discrimination of the stimuli, and the identification of the orientation of the stimuli. During all these processes visuoperceptual processes are important. Different authors have investigated the visual functions in children with spina bifida and hydrocephalus as well as in children with hydrocephalus only and have found impairments in those functions (Caines, Dahl, & Holmström, 2007; Ito et al., 2007; Shokunbi et al., 2002). Thereby, Shokunbi et al. (2002) "…suggests that hydrocephalus is the major factor in the genesis of cerebral visual impairment…" (Shokunbi et al., 2002, p. 742). They state that impairment of the visual pathways is due to the ventricular distension damage in the form of a structural or functional impairment. As they found these results for hydrocephalic children with myelomeningocele as well as for non-dysraphic hydrocephalic children, they concluded that the "…major factor in visual morbidity is the hydrocephalic process rather than the multi-focal brain changes of spinal dysraphism." (Shokunbi et al., 2002, p. 743). Another study by Ito et al. (1997) demonstrated a relationship between the verbal and performance intelligence score and visuoperceptual disturbance. Also, they were able to show a close relationship of visuoperceptual disturbances with the widening of lateral ventricles. Regarding these findings one could conclude that the impaired visuoperceptual processes in children with hydrocephalus might negatively influence the encoding processes in mental rotation tasks. The non-significant differences between children with spina bifida and hydrocephalus and children with hydrocephalus only were detected in the first experiment in the 0° condition. These findings support the study of Ito et al. (1997), when considering the influence of perceptual processes in mental rotation. As both groups consisted of children with hydrocephalus, both groups would show impairments in visuoperceptual processes and therefore no differences in the reaction times would be detectable. Due to the absence of a healthy control group in the first experiment the question remains whether the reaction times in the 0° condition match those of healthy children or whether reaction times differ from healthy children in the way that these children are faster than children with hydrocephalus. This aspect should be incorporated in following research to investigate possible differences between SBHC, HC, and healthy children. The before mentioned explanation regarding the 0° condition is obsolete when considering the differences between the two groups in the two rotated conditions, in which differences are obvious. It seems that in these conditions, the 90° and 180° condition, other processes influence the mental rotation performance.

Therefore, the mental rotation process is regarded next. The mental rotation process itself consists of mental rotation and judgment of parity. Thereby, both working memory processes and motor processes can influence the performance in this process. Initially the involvement of working memory processes is considered. During the mental rotation process itself as well as the judgment of parity processes the mental visualized image needs to be stored somehow to be then compared to the object of comparison. These are supposed to be processes in working memory, since the visuospatial sketchpad is associated with the manipulation of visual images (Gathercole et al., 2004). Although only few studies have investigated working memory in children with spina bifida, the results of these studies provide clues for the interpretation of mental rotation performance. While Boyer, Yeates, and Enrile (2006) investigated working memory and processing speed in children with spina bifida and shunt-treated hydrocephalus, they showed impairments in these abilities in those children. Their results indicate that children with spina bifida perform poorly on the tasks compared to a healthy control group and that they "… tend to respond in a way that avoids the working memory demands of the task…" (Boyer et al., 2006, p. 310). Additionally, the impairment of working memory in young adults with spina bifida was shown by Iddon et al. (2004). Additional, Mammarella et al. (2003) outlined that children with spina bifida are more impaired in visuospatial working memory, when passive processing is required, compared to tasks that rely more on active components. Whereas the previous mentioned studies indicate that children with spina bifida and hydrocephalus have impairments in working memory, Lindquist, Persson, Fernell, and Uvebrant (2011) showed that in their investigated population of hydrocephalus only a quarter of the participants performed in the low normal zone or below normal regarding working memory. Even though this indicates that although impairments in working memory are persistent in hydrocephalus, this does not account for hydrocephalus as a group. This assumption is supported by results of the study by Dennis et al. (2007), who stated that although hydrocephalus aggravate deficits in memory, the etiology of hydrocephalus needs to be considered, since different etiologies lead to variations in memory profiles.

The above mentioned results seem to suggest that differences in the angular disparities 90° and 180° in a mental rotation tasks between SBHC and HC children might be explainable on the basis of different working memory performance. Whereas in children with spina bifida working memory processes seem to be more impaired than in hydrocephalus only, this fact might lead to problems in the mental rotation process and the judgment of parity process when holding the mental rotated stimuli in memory while comparing this to the object of comparison. Since Dennis et al. (2007) point out that the etiology of hydrocephalus is related to memory deficits, children with acquired hydrocephalus are maybe less impaired in working memory processes than children with congenital hydrocephalus. Therefore they might perform better in mental rotation tasks. Yet, the results of Experiment 1 and other studies seem to refute this assumption. Since the differences in reaction times still remained significant after excluding the children with acquired hydrocephalus from the congenital HC group, the etiology of hydrocephalus and its mechanism of action on working memory seem to play no importance at least in mental rotation tasks. Additionally, Dennis, Hetherington, and Spiegler (1998) showed that children with brain tumors and variable hydrocephali are impaired in memory as well. This leads to the conclusion that the differences found in mental rotation performance in children with spina bifida and hydrocephalus and children with hydrocephalus only seem not to be due to impairments in working memory, but rather other processes appear to influence the different mental rotation performance in these two groups of children with neurological disorders. Although working memory has not been evaluated in the presented experiments, further research needs to consider the including of working memory measurements when addressing similar issues.

Based on the reflections on the involvement of working memory, other underlying processes need to be considered. As already mentioned in the discussion of Experiment 1 (compare chapter 5.3), the differences in the angular disparities of 90° and 180° might depend on motor components. Thereby it was stated that, based on evidence for the relationship of locomotion and cognition (Rendeli et al., 2002), early movement is associated with the ability to explore spatial relations and to develop spatial experiences that might be relevant to the development of spatial abilities later on in life. Therefore, children with HC might benefit from their spatial experiences regarding their mental rotation performance, whereas children with SBHC are at a disadvantage compared to HC children due to their impaired motor abilities associated with the neurological disorder. This issue it further addressed in the following paragraph.

Whereas previous in this chapter the 0° condition in mental rotation has already been addressed regarding perceptual processes, it is now addressed under the aspect of motor processes. Since to the 0° condition response selection and execution are assigned, one could conclude that differences occur due to these processes. But as no differences between the two groups were detectable for the 0° condition, this explanation lacks.

Due to the fact that research regarding the relationship between mental rotation performance and motor skills in children with hydrocephalus and children with spina bifida and hydrocephalus is lacking, a possible transfer from already existing studies to this relationship is envisaged. In a study by Steggemann, Engbert, and Weigelt (2011) participants with and without motor expertise for rotational movements were investigated regarding their mental rotation performance. While they found differences in the performance only for perspective transformations and not in general, this study indicates that participants with a specific expertise benefit from this regarding the mental rotation performance. Although further research is necessary to evaluate this relationship further, one might draw a transfer from these results to the two groups of experiment done within this PhD thesis. Since children with hydrocephalus could explore spatial relations due to their non-restricted motor abilities, they became “spatial-relation-experts” compared to children with spina bifida and hydrocephalus, who were not able to explore spatial relationships in a similar way due to the constrained motor abilities that are associated with spina bifida. Consequently, children with hydrocephalus benefit in the 90° and 180° condition from familiarity with those relations, whereas children with spina bifida lack familiarity of those spatial relationships.

When continuing this chain of thought one needs to deal with the different motor abilities in those children and whereupon these differences are linked to. Research has shown that locomotion is associated with better performance in spatial tasks (Campos, Anderson, & Telzrow, 2009; Schwarzer et al., 2012). Campos et al. (2009) confirmed their hypotheses that children with spina bifida, who are delayed in their locomotive development, are also delayed in the spatial tasks “object permanence task” and “following the point and gaze”. Additionally, Schwarzer et al. (2012) showed that mental rotation performance in infants is influenced by crawling, with more successful performance in mental rotation for crawlers compared to non-crawlers. They concluded that this might be explainable through the possibility to explore objects from different perspectives when the ability to crawl exists. As children with spina bifida in Experiment 1 started to crawl at least two months later than children with hydrocephalus, one can conclude that children with HC developed an advantage in spatial relations that might have persisted through further development and is still detectable at the age of 8 till 12. The persistence of these differences through childhood into early adolescence might be due to the often impaired or restricted walking abilities with which the children with spina bifida are faced. Since the ability of locomotion is often restricted to orthopedic aids, such as orthesis or wheelchairs, the motor development in children with spina bifida differ from that in children with hydrocephalus only. This assumption is supported by the study of Lomax-Bream, Barnes, Copeland, Taylor, and Landry (2007), who found impaired motor abilities, cognitive skills, and language skills in children with spina bifida. Thereby they distinguished further between those children who were shunt-treated or had higher levels of lesion from those without a shunt or lower lesion levels. Children who belonged to the first group showed poorer motor performance than the second group. Further evidence for the involvement of motor abilities in spatial organization is given by Rendeli et al. (2002). While children who were ambulatory performed better than those who were non-ambulatory, the authors state that “this could be connected with better visuomotor performance of space linked to the self-produced locomotion.” (Rendeli et al., 2002, p. 233). Consequently, it seems likely, that the deficits in motor development that occur in spina bifida are somehow responsible for the poorer mental rotation performance in children with spina bifida and hydrocephalus.

Based on the previous mentioned assumptions it seems that motor abilities do play a role in mental rotation performance. Although we did not rule out other possible effects on the detectable differences between children with spina bifida and hydrocephalus and children with hydrocephalus only, due to not testing, we showed the beneficial influence of motor training on mental rotation ability in children with spina bifida in Experiment 2. This issue will be addressed in more detail in the following chapter. Additionally, the influence of other underlying processes that might have influenced mental rotation performance is considered further in chapter 7.3.

7.2 Influence of training on mental rotation ability

Based on previous studies which have investigated the influence of juggling training on mental rotation performance successfully (Jansen et al., 2009; Jansen, Lange et al., 2011) and on studies that have shown that children with spina bifida show impaired mental rotation performance (Jansen-Osmann et al, 2008), it was assumed that children with spina bifida would profit likewise from juggling training regarding their mental rotation performance. The results of Experiment 2 confirmed this presumption in showing a significant reaction time gain for the experimental group compared to the control group.

While Experiment 2 showed a significant higher reaction time gain for the experimental group compared to the control group, the increase in reaction time was not linear, but rather consisted of a peak at 90° and a small decrease at 180°. This is in line with previous studies (Jansen-Osmann & Heil, 2007a), who also did not find a linear increase in reaction time between the two angular disparities. Further support for the non linear increase in reaction time is given by studies from Neely and Heath (2009, 2010). They supply evidence that transformations of 180° are in advantage in response planning compared to 90° (Neely & Heath, 2009). Furthermore, they ruled out that these results were influenced by the familiarity with the cardinal axes respectively the perceptual expertise with cardinal axes (Neely & Heath, 2010). They showed that these differences between the two angular disparities might be explained by a vector inversion strategy that is used in the 180° condition. This strategy is thought to be less demanding and therefore results in faster reaction times. Transferred on the results of Experiment 1 one could conclude that different solution strategies for solving the tasks have led to the non-linear increase in reaction time gain between the 90° and 180° condition.

Apart from the faster reaction times that obviously showed an improvement in mental rotation performance, the question arises whether the training affected specific stages of mental rotation. Therefore, the analysis of mental rotation speed was conducted. When considering the different stages of mental rotation mentioned by Shepard and Cooper (1982) and Heil and Rolke (2002) (compare chapter 2.1.2), the speed of mental rotation, which is measured as the slope of the regression, represents the mental rotation process itself. On the basis of the results found in Experiment 2 one can draw the conclusion that juggling training has a direct effect on the process of mental rotation itself. These results are in line with the study by Wiedenbauer and Jansen-Osmann (2007), who also found benefits of training on the mental rotation process itself. Furthermore, juggling training effects are also found for the perceiving or encoding processes as well as for decision making processes. Since the 0° condition also showed a significant difference between experimental and control group, the stages associated with it (perceptual processing, identification and discrimination of stimuli, identification of orientation, response selection, and execution; Amorim, Isableu, & Jarraya, 2006; Heil & Rolke, 2002; Shepard & Cooper, 1982) are influenced by training as well. Due to the reaction times in the follow-up test in the experimental group it is assumed that this effect lasts minimum as long as half a year after the training.

Consequently, juggling training causes a decrease in reaction times in chronometric mental rotation tests, an increase in mental rotation speed, and training effects on the mental rotation process itself as well as on encoding and decision making processes in children with spina bifida.

In the last paragraph the effects of juggling training on reaction times and mental rotation speed have been described. In the next paragraph the issue of motor training on mental rotation performance will be addressed.

Due to the close connection of motor processes and mental rotation (compare also chapter 2.1.3 as well as 2.2.2), motor training is considered to improve mental rotation training. One kind of training has already significantly proven to successfully improve mental rotation performance - juggling. Juggling is thought to be comparable to mental rotation because of similar underlying features. In both abilities cyclic activities are required as well as temporal and spatial constrains (Jansen et al., 2009). When juggling objects the hands move along trajectories that are somewhat elliptical to throw and catch each of the objects successfully (Post et al., 2000); mental rotation requires cyclic trajectory movements around the x, y, and z-axes to bring an object in the same position as the standard object.

The effectiveness of such training for children with spina bifida was verified in Experiment 2. Additionally, the results highlight the aspect that children with initially poorer mental rotation abilities benefit from training of spatial abilities (Rizzo et al., 2001). Compared to the manual computer training that was offered to children with spina bifida by Wiedenbauer and Jansen-Osmann (2007), juggling has the advantage of being more suitable in daily living because of less dependency on the availability of computers. Another major benefit of juggling training is the possibility of differentiation according to the individual abilities. Therefore, juggling seems to be especially suitable for children with spina bifida which are a heterogeneous group of participants.

Due to the fact that in children with spina bifida only two kinds of training have been investigated into until now, namely manual rotation training (Wiedenbauer & Jansen-Osmann, 2007) and juggling training (Lehmann & Jansen, 2012), the next paragraph will consider the differences between those trainings and what requirements a successful motor training needs to contain to influence mental rotation performance. Therefore, studies with adults as well as with healthy children and their transferability on children with spina bifida are considered.

To differentiate between whether motor trainings are suitable to improve mental rotation performance or not, one need to look into the requirements on motor skills of such trainings. The manual training used in the study by Wiedenbauer and Jansen-Osmann (2007) consisted of a joystick embedded in a box standing within reaching position for the participants. When grasping and turning the joystick requirements from the eye-hand coordination skill is needed. While the eyes perceive the inputs from the presented stimuli, and the hand manipulates the joystick, coordination of both actions is required to bring the stimulus into the right position. While the eyes are focused on specific points on the screen the arm movements are restricted to the joystick and the controlled directions. Based on these deliberations one can state that the results gained from the manual training used by Wiedenbauer and Jansen-Osmann (2007) are restricted to the study conditions. Additionally, one could describe the training used by Wiedenbauer and Jansen-Osmann (2007) principally speaking as a strictly manual training coupled with a visual stimulus.

In contrast to the just mentioned approach the juggling training that was used in Experiment 2 and inter alia by Jansen et al. (2009) is defined by increased requirements regarding coordinational aspects. While juggling requires eye-hand coordination as well, further constraints are given due to the additional movement executions compared to the manual training. Apart from eye-hand coordination, other coordinative abilities are required as well. Amongst others orientation abilities are needed. This enables a person to move oneself in relation to an object. Also the ability to differentiate is needed, which describes the ability to dose one movement regarding the already learned movements. Another aspect is reactivity, which is the ability to react in an appropriate way to different aspects that the task requires. And lastly the ability to coordinate movements form different parts of the body into one effective body movement (Weineck, 2010). All these different aspects of coordination are needed when performing juggling movements. One has to dose the throw out of the juggling material so that one can catch these materials with the other hand. Additionally, one has to coordinate two or three different materials, so that they move along the more or less elliptical paths (Post et al., 2000). Also, one has to coordinate the movements of the arms and the upper body to throw and catch the juggling material. These are only a few aspects of juggling in which coordinative aspects are required to demonstrate the influence of different parts of coordination in this movement. Especially children with spina bifida are faced with even higher coordinative requirements in juggling due to their impaired motor abilities. Since most of the training was performed on chairs or in wheelchairs respectively, the children needed to be more precise in throwing and catching because they could not adjust with compensating movements of the lower limps.

Due to the described coordinative aspects in both trainings and the success of both trainings regarding mental rotation performance, one can conclude that coordinative aspects seem to play an important role when considering a motor training effective for mental rotation ability. The involvement of coordination in mental rotation is further confirmed by several studies.

For example, Jansen and Heil (2010) investigated the relationship between motor development and mental rotation in 5-to 6-year-old children. While they found a relationship between motor skills and mental rotation, their regression analysis revealed that most of the variance was explained by a test that measured coordination skill and a fine motor skill task. Further support for the relevance of coordination skills in motor training on mental rotation performance is given by several studies with adults and different sports. Whereas Ozel, Larue, and Molinaro (2004) in general showed that athletes perform better than non-athletes in a mental rotation task, Moreau, Clerc, Mansy-Dannay, and Guerrién (2011) and Moreau, Clerc, Mansy-Dannay, and Guerrién (2012) investigated this aspect more specifically. Moreau et al. (2011) addressed the issue whether a better mental rotation performance is related to the level of expertise in particular sports, combat sport versus running. They did find such an influence of expertise of sports on mental rotation performance, but only for those sports with a high amount of coordination skill, whereas runners did not show such an effect. Subsequently, Moreau et al.

(2012) investigated the influence of two different types of sports on mental rotation performance. One kind of sports required mental rotation whereas the other one did not require mental transformations. After a 10 month training period wrestlers showed improvement in mental rotation performance, while runners did not improve in their performance. The influence of coordination skills on mental rotation ability was further confirmed by a study by Pietsch and Jansen (2012), who investigated the relationship between a standardized coordination test and mental rotation performance in a paper pencil test. Their results revealed that a faster performance in the coordination test is also associated with a better mental rotation performance.

The previously mentioned studies indicate that motor training with a large amount of coordination seems to positively influence mental rotation performance. Although this needs to be established further in additional studies, one can draw the conclusion that motor training with high requirements on coordination skills lead to improvements in mental rotation performance. While in the studies conducted by Moreau et al. (2011, 2012) and Pietsch and Jansen (2012) the coordinative aspects can be related to the movement of the whole body, the studies by Wiedenbauer and Jansen-Osmann (2007) and Lehmann and Jansen (2012) had coordinative aspects only in parts of the body. Therefore, it seems that the coordinative aspects of training can be related to the abilities of the participating people and therefore adapted to the actual abilities of the participants.

Apart from the previous mentioned similarities of the trainings used by Wiedenbauer and Jansen-Osmann (2007) and Lehmann and Jansen (2012) regarding coordinational aspects, one needs to consider the distinctions between the two trainings as well. While Wiedenbauer and Jansen-Osmann (2007) used a strictly manual rotation training that was coupled with visual stimuli, the training by Lehmann and Jansen (2012) was a strictly motor training. Moreover, it seems that one needs to distinguish between manual rotation trainings and motor training programs and sport programs respectively. It seems that both manual training coupled with visual stimuli (Wiedenbauer & Jansen-Osmann, 2007) and manual rotation without visual feedback (Frick et al., 2009) that is similar to the investigated spatial ability lead to an improvement. This can also be achieved with motor training that is based on sporting activities. Thus, the results of Experiment 2 together with the results of Ozel et al. (2004), Moreau et al. (2011, 2012), and Pietsch and Jansen (2012) indicate the importance of sport for cognitive and spatial abilities respectively. Hence, these results prepare a basis for further research regarding the influence of sports on spatial abilities.

Consequently, the results of Experiment 2 as well as the previously mentioned studies lead to the conclusion that children with spina bifida would probably benefit from other coordinative motor training regarding their mental rotation performance as well. This approach might be particularly interesting because of the demands that are associated with the illness spina bifida and that those children have to face. As most of the children participate in a rather huge amount of therapeutic interventions, a training that on the one hand could positively influence motor skills and on the other hand could be beneficial for cognitive abilities could probably reduce the amount of therapy and could contribute to the better integration of those children. Although such training needs further detailed research regarding the influence of motor abilities on different cognitive abilities, a few thoughts of possible motor trainings are introduced in the following paragraph.

Since children with spina bifida represent a heterogeneous group of participants, the training must be adjustable to individual needs without losing focus on the original intention. One possible training could be wheelchair basketball, in which a high coordination, mainly eye-hand coordination, is needed to control the wheelchair and basket ball simultaneously, while orientating oneself in the field and in relation to the own team as well as in relation to the opponent. As a constraint of wheelchair basketball one needs to consider that no rotational or elliptical movements of the arms are required and whether the movements associated with the pushing of the wheelchair are sufficient to influence mental rotation ability lacks scientific proofs. However, the imagination and spatial orientation required to throw the ball into the basket or the calculation of the trajectory of the ball when passing it to a team member might compensate for that and be beneficial for the development on mental rotation performance. Another sport in which particularly the eye-hand coordination is needed is wheelchair tennis. One has to position oneself in a suitable location with regard to the ball and then has to coordinate the movement of the hand with the racket considering the trajectory of the ball.

Apart from the variety of possible motor training that could be effective on mental rotation performance when considering only coordinative aspects, the requirements of such a motor training on cognitive abilities needs to be considered as well. The constraints of mental training as well as possible influences of working memory on mental rotation under the aspect of training are regarded in the next chapter.

7.3 Relationship between mental rotation and working memory

Whereas the previous chapter has dealt with the influence of training on mental rotation, the following deliberations are devoted to the relationship between working memory and mental rotation. Moreover, the topic of training is continued in this chapter under the premise of requirements of mental training to improve spatial abilities as well as the inclusion of motor training in this process.

The issue of working memory processes in mental rotation has been shortly addressed in chapter 7.1, where the possible reasons for the differences between children with spina bifida and hydrocephalus and children with hydrocephalus only in mental rotation performance were considered. Through that it was shown that working memory processes are most likely involved in the mental rotation process itself, as well as in the judgment of parity processes. This is true because a mentally visualized image created in the mental rotation process needs to be stored somehow so that it can then be compared to another stimuli. As Gathercole et al. (2004) stated that the visuospatial sketchpad is associated with the manipulation of visual images, one can conclude that working memory processes are involved in these stages of mental rotation. So far the involvement of working memory in mental rotation has not been investigated on a behavioural level. Based on the results of Experiment 3 and the apparent relationship of the visuospatial sketchpad and the phonological loop during mental rotation, the contribution of these processes are examined in this chapter.

When considering the involvement of the visuospatial sketchpad in mental rotation it should be stressed that several authors suggest a dichotomy of the visuospatial memory. For example, Logie (1995) differentiated between a “visual cache” and an “inner scribe”. Whereas the “visual cache” is thought to be responsible for information that concern form and colour, the “inner scribe” is somehow similar to the subvocal rehearsal processes of the phonological loop and is responsible for spatial changes and keeping those information available. In another study Logie and Pearson (1997) showed both visual and spatial working memory mature during childhood with a much steeper increase for the visual subcomponent related to the age of the children. Pickering, Gathercole, Hall, and Lloyd (2001) have taken another approach for different subsystems in visuospatial memory. Their experiments with 5-, 8-, and 10-year-old children lead to their assumption that rather the static and dynamic nature of a task than the visual and spatial attributes of a task are responsible for picking one of the two subcomponent of the visuospatial memory.

Hyun and Luck (2007) investigated the spatial and object subsystem in working memory regarding a mental rotation task. While they found an interference effect of mental rotation and object memory storage, no interference occurred when mental rotation and spatial working memory were investigated. They concluded that in a mental rotation task, in which spatial manipulation is involved, the visual information about the form that results of the manipulation of the stimuli is held in the object working memory and therefore it seems that "...mental rotation appears to involve dorsal stream operations that are applied to representations stored in the ventral stream object working memory subsystem." (Hyun & Luck, 2007, p. 158). The participation of both streams is in line with the findings of Carpenter et al. (1999). Even Bruyer and Scailquin (1998) suggested two subcomponents for the visuospatial sketchpad.

When considering the results of the above described studies against the background of the results of Experiment 3 in this PhD thesis, the following assumptions can be made. While our results revealed an involvement of the visuospatial sketchpad in mental rotation, this can be further regarded when considering the remarks of Pickering et al. (2001). They identify in their study that the Corsi block task, which was used to measure the visuospatial sketchpad in our experiment, samples two types of cognition namely spatial processing as well as dynamic processing. Transferred on the relationship between mental rotation and Corsi block task in our results this could mean that in mental rotation apart from spatial processes are also dynamic processes involved. This would lead to a reconsideration of the results of Hyun and Luck (2007), who did not find an involvement of the spatial subsystem in a mental rotation task. But due to the stimuli used in this study, as well as due to the methodical structure of our experiment, these assumptions are rather speculative and deserve more precise attention in future research. These should take into account a visual and static measurement of the visuospatial sketchpad.

Apart from the involvement of the visuospatial sketchpad in mental rotation Ang and Lee (2008) as well as Bruyer and Scailquin (1998) have found a connection between the central executive and mental rotation tasks. When investigating the visuospatial sketchpad with dual-task paradigm, Bruyer and Scailquin (1998) showed an impairment of mental rotation when spatial suppression was used, whereas articulatory suppression did not lead to impairment in the main task. Interestingly, they found the effect of spatial suppression only for the 0° condition. They explained these results with a possible involvement of resources of the central executive. Bruyer and Scailquin (1998) highlighted the importance of the visuospatial sketchpad in mental images and they further concluded that rotation of mental images seems to rely on processes of the central executive. Further confirmation of the involvement of central executive resources in mental rotation is given by Ang and Lee (2008). In their study with 8- and 11-year-old children the influence of a verbal suppression task on short-term memory, working memory, and spatial visualization was investigated. While they showed that the secondary task led to an impairment of the before mentioned processes, one can conclude that executive resources are involved in these tasks. Since the working memory task that was used in this experiment was a rotation task, the results of the study by Ang and Lee (2008) lead to the assumption that during mental rotation central executive resources are considered.

In Experiment 3 we did not find the involvement of the central executive in mental rotation. This might be due to age differences between the studies, since children in our experiment were between 3- and 6-years of age, whereas the children in the study by Ang and Lee (2008) were 8 and 11 years old. The measurement of working memory in children as young as our study is not as simple as in older children. Gathercole et al. (2004) as well as Roebers and Zoelch (2005) stated that the distinction and separability of the two subsystems visuospatial sketchpad and phonological loop in working memory is detectable in children as early as 4 years of age (Alloway et al., 2006). However, in children as young as 3 years of age, working memory research is somehow rare and only few attempts have been made. For example, Zoelch and Mähler (2012) reported about a study conducted by themselves with such young children. They confirmed the distinction for the two subsystems of working memory for children as young as 3 years of age, but highlighted the difficulty of capturing central executive processes. Therefore, the non-existing involvement of central executive processes in our experiment might be due to the age of the participants, as well as the problems of gathering these processes in this age of children. Consequently, this aspect needs to be taken into consideration when investigating mental rotation and working memory processes further.

However, we did find an involvement of the phonological loop processes in the mental rotation task. The phonological loop is differentiated into two subsystems which are the phonological store and an articulatory control process. Whereas the first mentioned subsystem holds acoustic or speech-based information available for 1 to 2 seconds, is the second subsystem responsible for "…maintain[ing] material within the phonological store by subvocal repetition, and it can take visually presented material such as words or nameable pictures and register them in the phonological store by subvocalization." (Baddeley, 1992, p. 558). Although Hasselhorn, Grube, and Mähler (2000), amongst others, state that the digit recall forward task rather measures the total capacity of the phonological loop, it might be that in our experiment the involvement of the phonological loop is rather attributable to processes of the articulatory control process than the phonological store. The possible basis for this assumption has already been presented in the discussion of Experiment 3 (compare pp. 77-78).

Contrary results regarding this explanation are given by the study of Ang and Lee (2008). They did not find an effect of articulatory suppression on mental rotation and therefore no involvement of the phonological loop in mental rotation. These results challenge the possible explanation of the storage of non-phonological inputs, here the pictures used in the mental rotation task, in the phonological loop through rehearsal processes. The different results in our study compared to other studies could be attributed to either the children´s age, the different development strategies for solving mental rotation tasks, or other possible explanations that might be more appropriate.

Gathercole and Hitch (1993) indicate that in children as young as four years of age, the phonological loop system with its division into two subsystems is already in place, but that the articulatory processes / rehearsal processes are rather less used and therefore, "…they are less likely to recode spontaneously visual material into phonological form…" (Gathercole & Hitch, 1993, p. 194). These results are further confirmed by Gathercole and Adams (1994). Resting upon this statement it needs to be considered which other relationship between mental rotation and the phonological loop might be more appropriate.

In the work by Baddeley (2000) and Baddeley and Hitch (1974) it has been stated that the subsystems, the phonological loop, as well as the visuospatial sketchpad, both are linked closely to the central executive. While the central executive is responsible for the coordination of the information from both slave systems, the subsystems are rather independent from each other. This division of the two subsystems, as well as the close connection to the central executive, has already been proven for children as young as four years of age (Gathercole et al., 2004; Gathercole & Pickering, 2000). Due to the close connection of the phonological loop to the central executive, as well as the rather unlikely usage of rehearsal processes of the phonological loop in young children, it might be possible that another explanation for our results in Experiment 3 could be possible. It might be that the work load of the task digit recall forward has rather initiated the "… operation of less highly specialized working memory subsystems such as the central executive" (Gathercole et al., 2004, p. 178) than the phonological loop itself. When continuing this thought the involvement of the phonological loop in mental rotation in Experiment 3 of this PhD might reflect the participation of central executive in mental rotation. Several statements support this assumption. First of all, the age of the children of our study is in accordance with the age that Gathercole and Hitch (1993) invoke. At this age the use of the subsystems of the phonological loop is not yet fully developed. Secondly, while Ang and Lee (2008) showed in their experiment the influence of a suppression task on working memory processes and a possible involvement of executive recourses in the rotation task, these results further support a possible connection between mental rotation processes and central executive resources. Due to the lack of evidence in research regarding mental rotation and the relationship of working memory processes, further studies need to clarify the previous assumption in more detail. Thereby the development of the different working memory processes during childhood as well as the participation of the different systems of working memory need to be considered in detail.

7.4 Working memory, training and mental rotation

Based upon the rather few studies regarding the relationship of working memory and mental rotation on a behavioural level, the relationship of working memory, motor abilities, and mental rotation has even less been considered in this context. Therefore, the next paragraphs are dedicated to possible effects of motor training on working memory and mental rotation, as well as effects of cognitive training on motor and mental rotation performance.

There are two possible variations of training that can be looked at when considering the relationship of mental rotation, motor skills, and working memory - a rather cognitive training or a motor training. The first paragraph is devoted to cognitive training, more precisely working memory training and spatial skill training, whereas afterwards motor training is addressed.

When considering the effects of working memory training a first look should be taken on the effectiveness of such training on cognitive tasks itself, here working memory capacity. Then the focused is turned on the effectiveness of such training on motor abilities and mental rotation performance. Whereas different studies suggest different results for working memory training, the efficiency might be best illustrated with a meta-analysis. Melby-Lervåg and Hulme (2012) conducted such a meta-analysis, in which different computerized working memory training programs were investigated in terms of effectiveness. Through that, their study showed surprising results when revealing indeed reliable improvements in verbal as well as nonverbal working memory tasks. However, they showed in the same study that the improvements were only detectable as short-term effects, but not as long-term effects. Additionally, the meta-analysis did not yield any transfer effects of working memory training on other skills such as arithmetic or word decoding. Different factors might have influenced the results of the meta-analysis and therefore need to be considered in future. For one thing the duration of training should be expanded to rather long-term training. Furthermore, while in the meta-analysis rather typically developing children were observed, the findings might be different for children with developmental, neurological or other disorders. Lastly, the age of children needs to be considered concerning developmental aspect. Since in younger children the neural systems undergo a developmental shift, the plasticity of these systems might lead to a larger effect in younger children than in older ones (Melby-Lervåg & Hulme, 2012). The results of this meta-analysis are rather puzzling and seem to indicate that working memory training might not lead to improvements in cognitive abilities, at least not in working memory capacity. This could lead to the conclusion that working memory training might not be effective to influence mental rotation performance regarding long term effects, since working memory processes are considered to be part of the underlying mental rotation processes. But since this is a rather speculative conclusion, further studies need to investigate this aspect in more detail.

Whereas working memory training seems to have a rather small and no outlasting effect on cognitive tasks or working memory capacity respectively, other studies did find effects of working memory training on additional tasks. For example, Studer (2011) examined the influence of working memory training and balance training on the abilities themselves and on possible transfer effects. Whereas one group attended a working memory training that was conducted as computer program, the other group participated in balance training. Participants of both groups performed cognitive as well as balance measurements at the beginning and the end of the training. Studer (2011) showed that working memory and balance training improved performance in the specific domain and additionally he was able to show that the working memory training led to improvement in balance performance. This effect was not only detectable as an immediate effect, but also as long term effect measured with a follow-up test. Whereas Studer investigated the influence of training on working memory and balance, Niederer et al. (2011) did not investigate the influence of training between those factors, but did a cross-sectional and longitudinal study. They found a relationship between dynamic balance and working memory. This specific conjunction between balance and working memory was also found by Wassenberg et al. (2005). The results of these studies support the assumption made in Experiment 3 of this doctoral thesis. Together these studies seem to deliver further evidence for the relationship between motor skills and cognitive abilities in kindergarteners and more precisely of working memory and balance in these children. Additionally, these studies suggest that the relationship between motor and cognitive skills might be specific to certain motor and particular cognitive tasks.

Due to the relationship between working memory and balance, found by Studer (2011), as well as mental rotation, found in Experiment 3 of this work, it might be the case that working memory training could affect mental rotation ability. But this assumption is rather speculative and lacks scientific evidence and therefore, further studies need to be conducted to address this issue and explain these relationships.

Apart from the impact of working memory training on balance and the possible effects on mental rotation, another kind of training might be suitable as well for improving the relationship between working memory, motor skills, and mental rotation. Due to the probable malleability of spatial skills, investigated by Uttal et al. (2012), it might be possible that training of the spatial skills could positively influence the triple relationship as well. The meta-analysis performed by Uttal et al. (2012) indicated that "…spatial skills are highly malleable, and that training in spatial thinking is effective, durable, and transferable." (Uttal et al., 2012, p.37). Thereby, these effects were seen in all their investigated categories of spatial skills. Additionally, the meta-analysis revealed that transfer effects were possible and that the type of training used to improve the spatial skills was not limited to specific training. The authors suggested that spatial skills are trainable in a variety of methods and therefore it seems that different methods can produce the same effect. Uttal et al. (2012) further suggested that spatial skills "…are obviously affected by the amount of information that can be held simultaneously in memory." (Uttal et al., 2012, p. 47). Therefore, the in the previously mentioned paragraph possible influence of working memory on mental rotation might be explained by this assumption. But since working memory training on mental rotation performance has not been investigated up till now, this needs to be clarified with scientific evidence.

Whereas the analysis of Uttal et al. (2012) did not reveal a significant age effect regarding the trainability of spatial skills during lifetime, this might be true to the standard error in the meta-analysis. Due to the lack of work regarding systematical comparisons of different age groups, there is a huge field for further research. Referred to the age group considered in Experiment 3, results for younger children are interesting to look at. This has been done inter alia by Newcombe (2010), who looked at different methodological approaches to improve spatial abilities in young children. She stated that with the use of variable opportunities (such as gesturing, the use of spatial words respective language by parents and teachers, puzzling, visualization, and games like Lego bricks or Tetris) the spatial abilities of young children can be encouraged and enhanced.

Huttenlocher, Levine, and Vevea (1998) did find an influence of the amount of school input on inter alia spatial operations in kindergartners and first graders. While the growth in the measured cognitive tasks was higher for those time periods when a greater amount of school input was received, they concluded that the amount of input is relevant for the improvement in different domains. Therefore, it seems that particularly in children the input that is provided especially has a positive effect on the improvement of spatial skills. Consequently, children should benefit from training regarding their spatial abilities and according to the assumption of Uttal et al. (2012), this might be also true and transferable for working memory processes.

Based on the depicted results regarding working memory training and spatial skill training, the following assumption for the relationship between working memory, mental rotation, and motor skills can be made: While it seems that working memory training has an effect on motor skills, particular on balance, it might also be associated to mental rotation improvement. Additionally, the training of spatial skills, as a representation of mental rotation, might also be effective on working memory performance. Both statements need to be proven with scientific research, which investigates the presented possible effects in more detail.

The relationship between working memory and motor abilities that has already been mentioned before, is addressed in the following paragraph again. Although the relationship between working memory, motor skills, and mental rotation has not been addressed so far, research considering the relationship between motor skills and working memory exists. For example, Piek et al. (2004) showed a significant association between motor coordination and working memory, after controlling for age, gender, and verbal IQ. Due to their measurement of motor coordination, no statement regarding differences between fine and gross motor skills could be made. Roebers and Kauer (2009) revealed a relationship between postural flexibility and Backwards Color Recall, but no such relationship between the Backward Color Recall and a fine motor task. Additionally, Michel, Roethlisberger, Neuenschwander, and Roebers (2011) found a relationship between motor coordination impairment and executive functions, but only for attention and inhibition and not for working memory. Thereby, the results of this study revealed a correlation between the working memory task and manual dexterity for those children having impairments in motor coordination, but not for the control group. These results indicate that the relationship between motor coordination and working memory might be due to specific aspects of motor coordination. Therefore, specific aspects, such as, for example, manual dexterity, might not be associated with working memory, whereas, for example, postural flexibility is related to working memory. Based on the connection between motor skills and cognitive skills, Rigoli, Piek, Kane, and Oosterlaan (2012) investigated motor coordination, working memory and academic achievement in adolescent participants. Their results revealed that the influence of motor coordination on academic achievement is mediated through working memory. This means that motor coordination "…has an indirect impact on learning outcome via WM." (Rigoli et al., 2012, p. 778).

The quoted studies indicate a relationship between motor coordination and working memory and encourage our results regarding this relationship in Experiment 3. Furthermore, the conjunction between those two abilities also indicates that it might be possible to influence one of the abilities through training of the other ability. Although this seems quite plausible based on studies such as the one conducted by Studer (2011), scientific evidence of the exact relationship between working memory and motor coordination is lacking and therefore this needs to be investigated in more detail. Although studies regarding this aspect are missing, the relationship between motor coordination and mental rotation has already been investigated to a certain amount. Evidence for the possible trainability of cognitive processes through motor training is given by the studies that investigated the influence of juggling training on mental rotation ability (Jansen et al., 2009; Jansen, Lange et al., 2010; Lehmann & Jansen, 2012). While these studies showed that mental rotation performance was improved through juggling, one can further conclude that maybe the juggling training improved working memory performance, which was expressed in the improved mental rotation performance. Evidence for this assumption is provided through the results of the mental rotation speed that was investigated in the study with children with spina bifida by Lehmann and Jansen (2012). Because Lehmann and Jansen showed an improvement in mental rotation speed from per- to posttest, which was only apparent in the experimental group, they revealed that those children improved their mental rotation process itself. Due to the involvement of working memory in exactly this process, the previously made connection between juggling and working memory could be true. However, since evidence for the mental rotation speed improvement in healthy children and adults is lacking, the assumption remains rather speculative, but provides an interesting approach for further studies.

Based on the studies mentioned and results in this chapter I would like to present some ideas on how motor training is believed should be conceptualized to be effective at improving cognitive abilities, such as working memory and mental rotation. Also, it will be shown which challenges it has to stand up to.

In line with Michel et al. (2011) an

> …intervention for children at risk or with deficits in the motor domain may benefit from a multidimensional approach. Apart from focusing on motor coordination skills, an intervention should include cognitive training of executive skills. Further, a screening of more specific precursors of academic skills, as phonological awareness or basic math competencies would be useful, as these have been shown to be predictive for later school success (Krajewski, & Schneider, 2009). (Michel et al., 2011, p. 168).

I would recommend this multidimensional approach as well, but not only for children with motor deficits, but also for children with restricted cognitive abilities and other diseases, such as neurological disorders. Due to the relationship between motor skills and cognitive skills, I am of the opinion that the interaction between these factors not only works in one direction, but will work both ways, although this has to be scientifically established. Based on these considerations a possible motor training should include motor tasks with requirements on coordinative aspects. These requirements should increase with progressing training. Additionally, the motor training should include tasks that address cognitive abilities such as executive skills, working memory, and spatial components. Examples for such tasks are motor task that require a specific presented stimuli that indicates which of several tasks need to be executed and which needs to be suppressed (executive skills), motor tasks that are accompanied with memory tasks (working memory), and motor tasks where for examples distances or other spatial relations are included (spatial skills). An example for the training of motor skills as well as executive skills could be a partner exercise. In that exercise, partner “A” stands with his back to partner “B”. On a command of “B”, “A” turns around and faces “B”. Depending on the color of the ball that “B” presents to “A”, a catching or throwing task has to be executed by “A”, and therefore, the partner has to react or inhibit an action respectively. Training of working memory could take place while exercising juggling. Before the juggling starts, the participant gets a number presented. While holding this number in memory, the participant starts to juggle and during the juggling gets presented further numbers, which he/she has to add to the previous number. The training of spatial skills can include, for example, throwing at aims that are positioned at different distances.

Although such requirements are often already included in motor trainings that are applied in therapy or in dealing with impaired children, the mechanism of action of specific motor components on specific cognitive abilities needs to be investigated more thoroughly to understand the underlying processes in more detail. Not until the mode of operation between the different components of working memory, motor skills, and spatial skills is fully understood is it possible to construct motor or cognitive programs that are especially adjusted for the needs of specific audiences. The comprehension of the underlying processes adds to the possibility to foster those children that need support with a multimodal approach of motor training, as well as cognitive training. Based on these requirements it might be possible to influence the children and their abilities in a positive way and consequently accomplish a better foundation for their educational career.

7.5 Summary and outlook

This work investigated mental rotation performance in children with neurological disorders, as well as the effects of juggling training in mental rotation performance in such children. Additionally, the connection between mental rotation, motor skills, and working memory was explored.

When comparing children with spina bifida and hydrocephalus with children with hydrocephalus only regarding their mental rotation performance, children with spina bifida revealed reduced mental rotation performance. This was demonstrated by slower reaction times in the rotated conditions (90° and 180°). Even when considering IQ and aetiology as possible treats, the differences persisted. Allowing for multiple possibilities to explain these differences, we came up with the impaired motor abilities in children with spina bifida as possible explanation. Therefore, the second experiment investigated the trainability of mental rotation performance through motor training, in form of juggling, in children with spina bifida. It was shown that due to such training mental rotation performance increased in children with spina bifida compared to a control group. Additionally, it was demonstrated that the improvement in mental rotation performance was dedicated to improvement in the mental rotation process itself, rather than other processes involved in mental rotation. Whereas the general improvement in mental rotation performance in children with spina bifida was shown, no differences were found between those children who were able to walk compared to those children that were restricted to wheelchairs. These results led to the conclusion that maybe not motor processes, but rather other underlying processes in the mental rotation process itself might be responsible for the detectable improvement and thus explain the differences in children with hydrocephalus with and without spina bifida. Therefore, the third experiment was concerned with the involvement of additional processes and motor processes in mental rotation. For that reason the relationship between mental rotation, motor skills, and working memory was investigated in preschool children. It was found that mental rotation performance was related to working memory processes, as well as balance and that the influence of motor skills diminished, when working memory processes were considered in this relationship.

The results of the studies add to the existing literature of mental rotation with regard to a better understanding of the reasons of impaired mental rotation performance in children with spina bifida, the trainability of mental rotation performance in such children, as well as to the underlying processes in mental rotation with regard to working memory processes.

On the one hand the results of Experiment 1 revealed that in children with spina bifida and hydrocephalus rather the spina bifida and the thereby associated impaired motor abilities are responsible for the impaired mental rotation performance than the hydrocephalus. On the other hand the results of Experiment 1 lead to the remaining question, whether other processes such as working memory capacity also play an important role in this performance. This is further supported by the results of Experiment 2, which revealed the possibility of trainability of mental rotation performance in children with spina bifida, but which also raise the question, why no differences were found between children who were restricted to a wheelchair compared to children who were able to walk. Due to these rather unexpected results regarding motor abilities and mental rotation performance in children with spina bifida, future research should include, next to the assessment of working memory processes in those children, a motor tasks assessment. Also, the underlying processes in mental rotation performance in such children should be investigated in more detail. While Experiment 3 indicated the involvement of working memory in healthy children, this has to be addressed in children with neurological disorders in more detail as well, since literature indicates that those children often show cognitive deficits due to possible brain malformations that are often associated with neurological disorders. Another aspect that should be addressed in children with spina bifida is the possibility of other motor trainings that could positively influence spatial skills in those children. Additionally, the long term effects of such training on the cognitive abilities of children with neurological disorders should be regarded.

The involvement of working memory processes in mental rotation revealed in Experiment 3 indicate that the underlying processes in mental rotation on a behavioral level, as well as in different developmental stages, need to be investigated in more detail. Whereas from a neuroscientific point of view the activation of different cognitive processes, such as working memory, has already been shown, this has to be confirmed in more detail on a behavioral level. Due to the study design in Experiment 3 as a correlation analysis, experimental designs need to confirm the results and extend them in more detail. Therefore, topics such as the involvement of the specific components of working memory in mental rotation with, for example, suppression tasks could be investigated. Also, the involvement of dynamic versus static components of the visuospatial sketchpad in mental rotation should be analyzed. Furthermore, the participation of working memory with a specific view to executive functions could also be addresses with regard to mental rotation performance or spatial abilities in general. Through that the aspect of motor skills could be integrated in this research question as well. More precisely, the questions which motor aspect influences which executive function need to be addressed.

Another interesting approach to the relationship between motor skills, cognitive/spatial skills, and working memory might be the investigation of neural networks. For example, Rigoli et al. (2012) suggests that the cerebellum might bear an important role in these processes. The involvement of the cerebellum in motor functions, as well as in cognitive tasks, has already been addressed by Diamond (2000). She stated that also the cerebellum has been associated with motor skills, evidence exists that an activation of the cerebellum exists during cognitive tasks as well. This counts particularly for cognitive tasks that create activation in the dorsolateral prefrontal cortex. Based on these results and further evidence of research with disabled patients, Diamond concluded that next to the prefrontal cortex the cerebellum plays a role in cognitive tasks as well. Furthermore, she suggested that the dorsolateral prefrontal cortex with its functions, such as holding information and manipulate theses information, as well as inhibit action, might as well play an important role in motor performance. The assumption of the additional involvement of neural regions that are typically associated with cognitive tasks in motor tasks is supported by Serrien et al. (2007). Based on these results the investigation of the underlying neural structures in the relationship between working memory, motor skills, and spatial abilities seems to be necessary to clarify this connection in more detail.

Although this thesis adds to the literature to understand the underlying processes in mental rotation as well as the relationship between cognitive and motor abilities, still significant questions remain that need to be answered to clarify the involved processes in more detail.

8. References

Aicardi, J. (2009). *Diseases of the nervous system in childhood*. London: Mac Keith Press.

Aksu, F. (2011). Entwicklungsstörungen und Fehlbildungen. In M. Sitzer, & H. Steinmetz (Eds.), *Lehrbuch Neurologie* [Textbook Neurology] (pp. 393-404). München: Urban & Fischer.

Alloway, T.P., Gathercole, S.E., & Pickering, S.J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development, 77*, 1698-1716.

Alloway, T.P., Gathercole, S.E., Willis, C., & Adams, A.-M. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology, 87*, 85-106.

Alloway, T.P., Rajendran, G., & Archibald, L.M.D. (2009). Working memory in children with developmental disorders. *Journal of Learning Disabilities, 42*, 372-382.

Amorim, M.-A., Isableu, B., & Jarraya, M. (2006). Embodied spatial transformations: "body analogy" for the mental rotation of objects. *Journal of Experimental Psychology: General, 135*, 327-347.

Ang, S.Y., & Lee, K. (2008). Central executive involvement in children´s spatial memory. *Memory, 16,* 918-933.

Anguera, J.A., Reuter-Lorenz, P.A., Willingham, D.T., & Seidler, R.D. (2010). Contributions of spatial working memory to visuomotor learning. *Journal of Cognitive Neuroscience, 22*, 1917-1930.

Ark, W.S. (2002). Neuroimaging studies give new insight to mental rotation. *Proceedings of the 35th Hawaii International Conference on System Sciences*.

Baddeley, A.D. (1992). Working memory. *Science, 255*, 556-559.

Baddeley, A.D. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology, 49A*, 5-28.

Baddeley, A.D. (2000). The episodic puffer: A new component of working memory? *Trends in Cognitive Science, 4*, 417-423.

Baddeley, A., & Hitch, G.J. (1974). Working memory. In: G.H. Bower (Ed.), *The psychology of learning and motivation; Advances in research and theory* (pp. 47-89). New York: Academic Press.

Band, G.P.H., & Miller, J. (1997). Mental rotation interferes with response preparation. *Journal of Experimental Psychology, 2*, 319-338.

Bear, M.F., Connors, B.W., & Paradiso, M.A. (2007). *Neuroscience. Exploring the Brain*. Philadelphia: Lippincott Williams & Wilkins.

Becker, P., Schaller, S., & Schmidtke, A. (1980). *Coloured Progressive Matrices*. Weinheim: Beltz-Test.

Berlit, P. (2007). *Basiswissen Neurologie* [Fundamental knowledge neurology]. Heidelberg: Springer.

Booth, J.R., MacWhinney, B., Thulborn, K.R., Sacco, K., Voyvodic, J., & Feldmann, H.M. (1999). Functional organization of activation patterns in children: Whole brain fMRI imaging during three different cognitive tasks. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 23*, 669-682.

Booth, J.R., MacWhinney, B., Thulborn, K.R., Sacco, K., Voyvodic, J.T., & Feldman, H.M. (2000). Developmental and lesion effects in brain activation during sentence comprehension and mental rotation. *Developmental Neuropsychology, 18*, 139-169.

Boyer, K.M., Yeates, K.O., & Enrile, B.G. (2006). Working memory and information processing speed in children with myelomeningocele and shunted hydrocephalus: Analysis of the Children´s Paced Auditory Serial Addition Test. *Journal of the International Neuropsychological Society, 12,* 305-313.

Brookshire, B.L., Fletcher, J.M., Bohan, T.P., Landry S.H., Davidson, K.C., & Francis, D.J. (1995). Verbal and nonverbal skill discrepancies in children with hydrocephalus: A five-year longitudinal follow up. *Journal of Pediatric Psychology, 60*, 758-800.

Bruyer, R., & Scailquin, J.-C. (1998). The visuospatial sketchpad for mental images: Testing the multicomponent model of working memory. *Acta Psychologica, 98*, 17-36.

Caines, E., Dahl, M., & Holmström, G. (2007). Longterm oculomotor and visual function in spina bifida cystica: A population-based study. *Acta Ophthalmologica Scandinavica, 85*, 662-666.

Campos, J.J., Anderson, D.I., Barbu-Roth, M.A., Hubbard, E.M., Hertenstein, M.J., & Witherington, D. (2000). Travel broadens the mind. *Infancy, 1,* 149-219.

Campos, J.J., Anderson, D.I., & Telzrow, R. (2009). Locomotor experience influences the spatial cognitive development of infants with spina bifida. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie, 41,* 181-188.

Carpenter, P.A., Just, M.A., Keller, T.A., Eddy, W., & Thulborn, K. (1999). Graded functional activation in the visuospatial system with the amount of task demand. *Journal of Cognitive Neuroscience, 11*, 9-24.

Cohen, M.S., Kosslyn, S.M., Breiter, H.C., DiGirolamo, G.J., Thompson, W.L., Anderson, A.K., … Belliveau, J.W. (1996). Changes in cortical activity during mental rotation: A mapping study using functional MRI. *Brain, 119*, 89-100.

Cooper, L.A., & Shepard, R.N. (1973). Chronometric studies of the rotation of mental images. In: W.G. Chase (Ed.), *Visual information processing* (pp. 75-176). Oxford: Academic.

Cowen, N. (1999). An embedded-processes model of working memory. In A. Miyake, & P. Shah (Eds.), *Models of working memory: mechanisms of active maintenance and executive control* (pp. 61-101). Cambridge: Cambridge University Press.

Del Bigio, M.R. (1993). Neuropathological changes caused by hydrocephalus. *Acta Neuropathologica, 85*, 573-585.

Démonet, J.-F., Taylor, M., & Chaix, Y. (2004). Developmental dyslexia. *The Lancet, 363*, 1415-1460.

Dennis, M., Edelstein, K., Copeland, K., Frederick, J., Francis, D.J., Hetherington, R., … Fletcher, J.M. (2005a). Covert orienting to exogenous and endogenous cues in children with spina bifida. *Neuropsychologica, 43*, 976-987.

Dennis, M., Fletcher, J.M., Rogers, T., Hetherington, R., & Francis, D.J. (2002). Object-based and action-based visual perception in children with spina bifida and hydrocephalus. *Journal of the International Neuropsychological Society, 8*, 95-106.

Dennis, M., Francis, D.J., Cirino, P.T., Schachar, R., Barnes, M.A., & Fletcher, J.M. (2009). Why IQ is not a covariate in cognitive studies of neurodevelopmental disorders. *Journal of the International Neuropsychological Society, 15*, 331-343.

Dennis, M., Hetherington, C.R., & Spiegler, B.J. (1998). Memory and attention after childhood brain tumors. *Medical and Pediatric Oncology Supplement, 1*, 25-33.

Dennis, M., Jewel, D., Drake, J., Misakyan, T., Spiegler, B., Hetherington, R., … Barnes, M. (2007). Prospective, declarative, and nondeclarative memory in young adults with spina bifida. *Journal of the International Neuropsychological Society, 13,* 312-323.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*, 44-56.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: Changes in grey matter induced by training. *Nature, 427*, 311-312.

Eisenegger, C., Herwig, U., & Jäncke, L. (2007). The involvement of primary motor cortex in mental rotation revealed by transcranial magnetic stimulation. *European Journal of Neuroscience, 25*, 1240-1244.

Engle, R.W., Kane, M.J., & Tuholski, S.W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake, & P. Shah (Eds.), *Models of working memory: mechanisms of active maintenance and executive control* (pp. 102-134). Cambridge: Cambridge University Press.

Eriksen, C.W., & Schultz, D.W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics, 25*, 249-263.

Ertl-Wagner, B. (2007). *Pädiatrische Neuroradiologie* [Paediatric neuroradiology]. Heidelberg: Springer.

Estes, D. (1998). Young children´s awareness of their mental activity: The case of mental rotation. *Child Development, 69*, 1345-1360.

Fletcher, J.M., Copeland, K., Frederick, J.A., Blaser, S.E., Kramer, L.A., Northrup, H., … Dennis, M. (2005). Spinal lesion level in spina bifida: A source of neural and cognitive heterogeneity*. Journal of Neurosurgery: Pediatrics, 102*, 268-679.

Fletcher, J.M., Francis, D.J., Thompson, N.M., Davidson, K.C., & Miner, M.E. (1992). Verbal and nonverbal skill discrepancies in hydrocephalic children. *Journal of Clinical and Experimental Neuropsychology, 14*, 593-609.

Foreman, N., Stanton, D., Wilson, P.N., & Duffy, H.E. (2003). Spatial knowledge of a real school environment acquired from virtual or physical models by able-bodied children and children with physical disabilities. *Journal of Experimental Psychology: Applied, 9*, 67- 74.

Frick, A., Daum, M.M., Walser, S., & Mast, F.W. (2009). Motor processes in children´s mental rotation. *Journal of cognition and development, 10*, 18-40.

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children´s imagery: The case of mental rotation of hands. *Developmental Science, 8*, 402-408.

Gathercole, S.E., & Adams, A.-M. (1994). Children´s phonological working memory: Contributions of long-term knowledge and rehearsal. *Journal of Memory and Language, 33*, 672-688.

Gatercole, S.E., & Hitch, G.J. (1993). Developmental changes in short-term memory: A revised working memory perspective. In A. Collins, S.E. Gathercole, M.A. Conway, & P.E. Morris (Eds.), *Theories of memory* (pp. 189-210). Hove: Lawrence Erlbaum.

Gathercole, S.E., & Pickering, S.J. (2000). Assessment of working memory in six- and seven-year old children. *Journal of Educational Psychology, 92*, 377-390.

Gathercole, S.E., Pickering, S.J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*, 177-190.

Geary, D.C., Saults, S.J., Liu, F., & Hoard, M.K. (2000). Sex differences in spatial cognition, computational fluency, and arithmetical reasoning. *Journal of Experimental Child Psychology, 77*, 337-353.

Gerrig, R.J., & Zimbardo, P.G. (2008). *Psychology and Life*. Boston, Mass: Pearson/Allyn and Bacon.

Hahn, N., Jansen, P., & Heil, M. (2010a). Preschoolers´ mental rotation: Sex differences in hemispheric asymmetry. *Journal of Cognitive Neuroscience, 22,* 1244-1250.

Hahn, N., Jansen, P., & Heil, M. (2010b). Preschoolers´ mental rotation of letters: Sex differences in hemispheric asymmetry. *Cognitive Neuroscience, 1,* 261-267.

Hampton, L.E., Fletcher, J.M., Cirino, P.T., Blaser, S., Kramer, L.A., Drake, J., & Dennis, M. (2011). Hydrocephalus status in spina bifida: An evaluation of variations in neuropsychological outcomes. *Journal of Neurosurgery: Pediatrics, 8*, 289-298.

Harris, I.M., Egan, G.F., Sonkkila, C., Tochon-Danguy, H.J., Paxinos, G., & Watson, J.D.G. (2000). Selective right parietal lobe activation during mental rotation: A parametric PET study. *Brain, 123*, 65-73.

Hasselhorn, M., Grube, D., & Mähler, C. (2000). Theoretisches Rahmenmodell für ein Diagnostikum zur differentiellen Funktionsanalyse des phonologischen Arbeitsgedächtnisses. In: M. Hesselhorn, W. Schneider, & H. Marx (Eds), *Diagnostik von Lese-Rechtschreibschwierigkeiten*. Tests und Trends [Diagnostics of dyslexia. Tests and Trends.], N.F. Band 1. Jahrbuch der pädagogischen-psychologischen Diagnostik (pp. 167-181). Göttingen: Hogrefe.

Hegarty, M., & Kozhevnikov, M. (1999). Types of visual-spatial representations and mathematical problem solving. *Journal of Educational Psychology, 91*, 684-689.

Heil, M., Rauch, M., & Hennighausen, E. (1998). Response preparation begins before mental rotation is finished: Evidence form event-related brain potentials. *Acta Psychologica, 99*, 217-232.

Heil, M., & Rolke, B. (2002). Towards a chronopsychophysiology of mental rotation. *Psychophysiology, 39*, 414-422.

Heil, M., Rösler, F., Link, M., & Bajric, J. (1998). What is improved if a mental rotation task is repeated – the efficiency of memory access, or the speed of a transformation routine? *Psychological Research, 61*, 99-106.

Huttenlocher, J., Levine, S., & Vevea, J. (1998). Environmental input and cognitive growth: A study using time-period comparisons. *Child Development, 69,* 1012-1029.

Hyun, J.-S., & Luck, S.J. (2007). Visual working memory as substrate for mental rotation. *Psychonomic Bulletin & Review, 14*, 154-158.

Iddon, J.L., Morgan, D.J.R., Loveday, C., Sahakian, B.J., & Pickard, J.D. (2004). Neuropsychological profile of young adults with spina bifida with or without hydrocephalus. *Journal of Neurology, Neurosurgery, & Psychiatry, 75*, 1112-1118.

Ito, J., Saijo, H., Araki, A., Tanaka, H., Tasaki, T., Cho, K., & Miyamoto, A. (1997). Neuroradiological assessment of visuoperceptual disturbance in children with spina bifida and hydrocephalus. *Developmental Medicine & Child Neurology, 39,* 385-392.

Jacobs, R., Northam, E., & Anderson, V. (2001). Cognitive Outcome in children with myelomeningocele and perinatal hydrocephalus: A longitudinal perspective. *Journal of Developmental and Physical Disabilities, 13,* 389-405.

Jansen, P., & Heil, M. (2010). The relation between motor development and mental rotation ability in 5-6 years old children. *European Journal of Developmental Science, 4*, 66-74.

Jansen, P., Lange, L.F., & Heil, M. (2011). The influence of juggling on mental rotation performance in children. *Biomediacal Human Kinetics, 3*, 18-22.

Jansen, P., Schmelter, A., Kasten, L., & Heil, M. (2011). Impaired mental rotation performance in overweight children. *Appetite, 56*, 766-769.

Jansen, P., Titze, C., & Heil, M. (2009). The influence of juggling on mental rotation performance. *International Journal of Sport Psychology, 40*, 351-359.

Jansen-Osmann, P., & Heil, M. (2007a). Suitable stimuli to obtain (no) gender differences in the speed of cognitive processes involved in mental rotation. *Brain & Cognition, 64*, 217-227.

Jansen-Osmann, P., & Heil, M. (2007b). Developmental aspects of parietal hemispheric asymmetry during mental rotation. *Neuroreport, 18,* 175-178.

Jansen-Osmann, P., Wiedenbauer, G., & Heil, M. (2008). Spatial cognition and motor development: A study of children with spina bifida. *Perceptual and Motor Skills, 106*, 436-446.

Jolicœur, P., Regehr, S., Smith, L.B.J.P., & Smith, G.N. (1985). Mental rotation of representations of two-dimensional and three-dimensional objects. *Canadian Journal of Psychology, 39*, 100-129.

Jordan, K., Heinze, H.-J., Lutz, K., Kanowski, M., & Jäncke, L. (2001). Cortical activations during the mental rotation of different visual objects. *NeuroImage, 13*, 143-152.

Jordan, K., Wüstenberg, T., Heinze, H.-J., Peters, M, & Jäncke, L. (2002). Women and men exhibit different cortical activation patterns during mental rotation tasks. *Neuropsychologia, 40*, 2397-2408.

Kail, R., & Park, Y.-S. (1990). Impact of practice on speed of mental rotation. *Journal of Experimental Child Psychology, 49*, 227-244.

Kail, R., Pellegrino, J., & Carter, P. (1980). Developmental changes in mental rotation. *Journal of Experimental Child Psychology, 29*, 102-116.

Kaufmann, L., Landerl, M., Mazzoldi, M., Moeller, K., Pastore, N., & Salandin, M. (2008). *Neuropsychologisches Screening für 5-11-jährige - BVN/NPS 5-11 -* [Neuropsychological Screening for 5- to 11-year olds]. Trento: Erickson.

Koshino, H., Carpenter, P.A., Keller, T.A., & Just, M.A. (2005). Interactions between the dorsal and the ventral pathways in mental rotation: An fMRI study. *Cognitive, Affective, & Behavioural Neuroscience, 5,* 54-66.

Kosslyn, S.M., Digirolamo, G.J., Thompson, W.L., & Alpert, N.M. (1998). Mental rotation of objects versus hands: Neural mechanisms revealed by positron emission tomography. *Psychophysiology, 35*, 151-161.

Kosslyn, S.M., Margolis, J.A., Barrett, A.M., Goldknopf, E.J., & Daly, P.F. (1990). Age differences in imagery abilities. *Child Development, 61*, 995-1010.

Kosslyn, S.M., Thompson, W.L., Wraga, M., & Alpert, N.M. (2001). Imagining rotation by endogenous versus exogenous forces: Distinct neural mechanism. *Neuroreport, 12*, 2519-2525.

Krüger, M. & Krist, H. (2009a). Verknüpfung von Vorstellung und Motorik in der Entwicklung: Die mentale Transformation bei Darstellungen von Händen [Integration of imagery and motor processes in development: Mental transformation with pictures of hands]. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie, 41*, 198-206.

Krüger, M., & Krist, H. (2009b). Imagery and motor processes – when are they connected? The mental transformation of body parts in development. *Journal of Cognition and Development, 10*, 239-261.

Kucian, K., von Aster, M., Loenneker, T., Dietrich, T., Mast, F.W., & Martin, E. (2007). Brain activation during mental rotation in school children and adults. *Journal of Neural Transmission, 114*, 675-686.

Lehmann, J., & Jansen, P. (2012). The influence of joggling on mental rotation performance in children with spina bifida. *Brain and Cognition, 80*, 223-229.

Linn, M.C., & Petersen, A.C. (1985). Emergence and characterization of sex differences in spatial ability: a meta-analysis. *Child Development, 56,* 1479-1498.

Lindquist, B., Carlsson, G., Persson, E.-K., & Uvebrant, P. (2005). Learning disabilities in a population-based group of children with hydrocephalus. *Acta Paediatrica, 94*, 878-883.

Lindquist, B., Persson, E.-K., Fernell, E., & Uvebrant, P. (2011). Very long-term follow-up of cognitive function in adults treated in infancy for hydrocephalus. *Child´s Nervous System, 27,* 597-601.

Lindquist, B., Persson, E.-K., Uvebrant, P., & Carlsson, G. (2008). Learning, memory and executive functions in children with hydrocephalus. *Acta Paediatrica, 97*, 596-601.

Lindquist, B., Uvebrant, P., Rehn, E., & Carlsson, G. (2009). Cognitive functions in children with myelomeningocele without hydrocephalus. *Child`s Nervous System, 25*, 969-975.

Logie, R.H. (1995). *Visuo-spatial working memory*. Hove: Lawrence Erlbaum.

Logie, R.H. (2003). Spatial and visual working memory: A mental workspace. In: D. Irwin, & B. Ross (Eds). *The Psychology of Learning and Motivation: Cognitive Vision, Volume 42* (pp. 37-78). San Diago: Academic Press.

Logie, R.H., & Pearson, D.G. (1997). The inner eye and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology, 9*, 241-257.

Loh, P.R., Piek, J.P., & Barrett, N.C. (2011). Comorbid ADHD and DCD: Examining cognitive functions using the WISC-IV. *Research in Developmental Disabilities, 32*, 1260-1269.

Lohman, D.F. (1979). *Spatial ability: review and re-analysis of the correlational literature.* Stanford University technical report No. 8.

Lomax-Bream, L.E., Barnes, M. Copeland, K., Taylor, H.B., & Landry, S.H. (2007). The impact of spina bifida on development across the first 3 years. *Developmental Neuropsychology, 3*, 1-20.

Mammarella, N., Cornoldi, C., & Donadello, E. (2003). Visual but not spatial working memory deficit in children with spina bifida. *Brain and Cognition, 53*, 311-314.

Mamor, G.S. (1975). Development of kinetic images: When does the child first represent movement in mental images?. *Cognitive Psychology, 7*, 548-559.

Mamor, G.S. (1977). Mental rotation and number conservation: Are they related?. *Developmental Psychology, 13*, 320-325.

Masuhr, K.F., & Neumann, M. (2007). *Neurologie* [Neurology]. Stuttgart: Thieme.

Melby-Lervåg, M., & Hulme, C. (2012). Is working memory training effective? A meta-analytic review. *Developmental Psychology*. Advance online publication. doi:10.1037/a0028228

Merigan, W.H., & Maunsell, J.H.R. (1993). How parallel are the primate visual pathways? *Annual Review of Neuroscience, 16*, 369-402.

Meyer, M.L., Salimpoor, V.N., Wu, S.S., Geary, D.C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences, 20*, 101-109.

Michel, E., Roethlisberger, M., Neuenschwander, R., & Roebers, C.M. (2011). Development of cognitive skills in children with motor coordination impairments at 12-month follow-up. *Child Neuropsychology, 17*, 151-172.

Mishkin, M., Ungerleider, L.G., & Macko, K.A. (1983). Object vision and spatial vision: two cortical pathways. *Trends in Neuroscience, 6,* 414-417.

Montello, D.R. (1993). Scale and multiple psychologies of space. In: A.U. Frank, & I. Campari (Eds), *Spatial information theory: A theoretical basis for GIS* (pp. 312-321) Berlin: Springer.

Moore, D.S., & Johnson, S.P. (2008). Mental rotation in human infants: A sex difference. *Psychological Science, 19*, 1063-1066.

Moreau, D., Clerc, J., Mansy-Dannay, A., & Guerrién, A. (2011). Spatial abilities and motor performance: Assessing mental rotation processes in elite and novice athletes. *International Journal of Sport Psychology, 42*, 525-547.

Moreau, D., Clerc, J., Mansy-Dannay, A., & Guerrién, A. (2012). Enhancing spatial ability through sport practice: Evidence for an effect of motor training on mental rotation performance. *Journal of Individual Differences, 33*, 83-88.

Neely, K.A., & Heath, M. (2009). Visuomotor mental rotation: Reaction time is not a function of the angle of rotation. *Neuroscience Letters, 463*, 194-198.

Neely, K.A., & Heath, M. (2010). Visuomotor mental rotation: Reaction time is determined by the complexity of the sensorimotor transformations mediating the response. *Brain Research, 1366*, 129-140.

Newcombe, N.S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator: Summer 2010*, 29-43.

Newcombe, N.S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain and Education, 4,* 102-111.

Niederer, I., Kriemler,, S., Gut, J., Hartmann, T., Schindler, C., Barral, J., & Puder, J.J. (2011). Relationship of aerobic fitness and motor skills with memory and attention in preschoolers (Ballabeina): A cross-sectional and longitudinal study. *BioMed Central Pediatics*, 11:34. doi:10.1186/1471-2431-11-34

Niethard, F.U., & Pfeil, J. (2009). *Orthopädie und Unfallchirurgie* [Orthopaedics and trauma surgery]. Stuttgart: Thieme.

Oswald, W.D. & Roth, E. (1987). *Der Zahlen-Verbindungs-Test-ZVT-*. [The Connecting Number Test] (2nd ed.). Göttingen: Hogrefe.

Ozel, S., Larue, J., & Molinaro, C. (2004). Relation between sport and spatial imagery: Comparison of three groups of participants. *The Journal of Psychology: Interdisciplinary and Applied, 138,* 49-64.

Pangelinan, M.M., Zhang, G., VanMeter, J.W., Clark, J.E., Hatfield, B.D., & Haufler, A.J. (2011). Beyond age and gender: Relationships between cortical and subcortical brain volumne and cognitive-motor abilities in school-age children. *NeuroImage, 54*, 3093-3100.

Paschke, K., Jordan, K., Wüstenberg, T., Baudewig, J., & Müller, J.L. (2012). Mirrored or identical – is the role of visual perception underestimated in the mental rotation process of 3D-objects?: A combined fMRI-eye tracking-study. *Neuropsychologia, 8*, 1844-1851.

Petermann, F. (Hrsg.). (2009). *Movement Assessment Battery for Children-2 (M-ABC-2)* (2.veränd. Auflage). Frankfurt am Main: Pearson Assessment.

Petermann, F., & Petermann, U. (Hrsg.).(2010). *HAWIK-IV. Hamburg-Wechsler-Intelligenztest für Kinder – IV*. [Hamburg-Wechsler-Intelligence test for children] 3., ergänzte Auflage. Bern: Hubert.

Peters, M., Chrisholm, P., & Laeng, B. (1995). Spatial ability, student gender and academic performance. *Journal of Engineering Education, 84*, 60-73.

Peters, M., Laeng, B., Latham, K., & Jackson, M. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*, 39-58.

Piaget, J., & Inhelder, B. (1956). *The child´s conception of space*. London: Routledge and Kegan Paul.

Piaget, J., & Inhelder, B. (1971). *Mental imagery in the child*. New York: Basic Books.

Pickering, S.J., Gathercole, S.E., Hall, M., & Llyod, S.A. (2001). Development of memory for pattern and path: Further evidence for the fractionation of visuo-spatial memory. *The Quarterly Journal of Experimental Psychology, 54A*, 397-420.

Piek, J.P., Dyck, M.J., Nieman, A., Anderson, M., Hay, D., Smith, L.M., … Hallmayer, J. (2004). The relationship between motor coordination, executive functioning and attention in school aged children. *Archives of Clinical Neuropsychology, 19*, 1063-1076.

Pietsch, S., & Jansen, P. (2012). The relationship between coordination skill and mental rotation ability. In: C. Stachniss, K. Schill, D. Utall (Eds). *Spatial cognition 2012* (pp. 173-181). Heidelberg: Springer.

Podzebenko, K., Egan, G.F., & Watson, J.D.G. (2002). Widespread dorsal stream activation during a parametric mental rotation task, revealed with functional magnetic resonsonance imaging. *NeuroImage, 15,* 547-558.

Post, A.A., Daffertshofer, A., & Beek, PJ. (2000). Principal components in three-ball cascade juggling. *Biological Cybernetics, 82,* 143-152.

Quaiser-Pohl, C., Rohe, A., & Amberger, T. (2010). The Solution strategy as an indicator of the developmental stage of pre-school children´s mental-rotation ability. *Journal of Individual Differences, 31*, 95-100.

Raabe, A., & Steinmetz. (2011). Erkrankungen des Liquorkreislaufs. In M. Sitzer, & H. Steinmetz (Eds), *Lehrbuch Neurologie* [Textbook Neurology] (pp. 289-294). München: Urban & Fischer.

Ramirez, G., Gunderson, E.A., Levine, S.C., & Beilock, S.L. (2012). Spatial anxiety relates to spatial abilities as a function of working memory in children. *The Quarterly Journal of Experimental Psychology, 65*, 474-487.

Raven, J.C., Court, J., & Raven, J.Jr. (1976). *Coloured progressive matrices. German version of Schmidtke, A., Schaller, S., & Becker, P. (1980).* Weinheim: Beltz.

Reitan, R.M. (1956). *Trail making test. Manual for administration, scoring, and interpretation*. Indianapolis: Indiana University Press.

Rendeli, C., Salvaggio, E., Sciascia Cannizzaro, G., Bianchi, E., Caldarelli, M., & Guzzetta, F. (2002). Does locomotion improve the cognitive profile of children with meningomyelocele?. *Child´s Nervous System, 18*, 231-234.

Richter, W., Somorjai, R., Summers, R., Jarmasz, M., Menon, R.S., Gati, J.S., … Kim S.-G. (2000). Motor area activity during mental rotation studied by time-resolved single-trial fMRI. *Journal of Cognitive Neuroscience, 12,* 310-320.

Rigoli, D., Piek, J.P., Kane, R., & Oosterlaan, J. (2012). Motor coordination, working memory, and academic achievement in a normative adolescent sample: Testing a mediation model. *Archives of Clinical Neuropsychology, 27*, 766-780.

Rizzo, A.A., Buckwalter, J.G., McGee, J.S., Bowerly, T., van der Zaag, C., Neumann, U., … Chua, C. (2001). Virtual environments for assessing and rehabilitating cognitive/functional performance: A review of projects at the USC Integrated Media Systems Center. *Teleoperators and Virtual Environments, 10*, 359-374.

Roebers, C., & Kauer, M. (2009). Motor and cognitive control in a normative sample of 7-year-olds. *Developmental Science, 12*, 175-181.

Roebers, C.M., & Zoelch, C. (2005). Erfassung und Struktur des phonologischen und visuell-räumlichen Arbeitsgedächtnisses bei 4-jährigen Kindern [Assessment and structure of phonological and visual-spatial working memory in 4-year old children]. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie, 37*, 113-121.

Roisson, B., & Pourtois, G. (2004). Revisiting Snodgrass and Vanderwart´s object pictorial set: The role of surface detail in basic-level object recognition. *Perception, 33*, 217-236.

Rogosa, D., Brandt, D., & Zimowski, M. (1982). A growth curve approach of the measurement of change. *Psychological Bulletin, 92*, 726-748.

Ruthruff, E., & Miller, J. (1995). Can mental rotation begin before perception finishes? *Memory & Cognition, 23*, 408-424.

Rüsseler, J., Scholz, J., Jordan, K., & Quaiser-Pohl, C. (2005). Mental rotation of letters, pictures, and three-dimensional objects in german dyslexic children. *Child Neuropsychology, 11*, 497-512.

Sack, A.T., Lindner, M., & Linden, D.E.J. (2007). Object- and direction-specific interference between manual and mental rotation. *Perception & Psychophysics, 69,* 1435-1449.

Sanz de Acedo Lizarraga, M.L., & García Ganuza, J.M. (2003). Improvement of mental rotation in girls and boys. *Sex Roles, 49*, 277-286.

Scholz, J., Klein, M.C., Behrens, T.E.J., & Johansen-Berg, H. (2009). Training induces changes in white-matter architecture. *Nature Neuroscience 12*, 1370-1371.

Schwarzer, G., Freitag, C., Buckel, R., & Lofruthe, A. (2012). Crawling is associated with mental rotation ability in 9-month-old infants. *Infancy,* 1-10.

Serrien, D.J., Ivry, R.B., & Swinnen, S.P. (2007). The missing link between action and cognition. *Progress in Neurobiologogy, 82*, 95-107.

Shepard, R.N., & Cooper, L.A. (1982). *Mental images and their transformations*. Cambridge: MIT Press.

Shepard, R.N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*, 701-703.

Shokunbi, M.T., Odebode, T.O., Agbeja-Baiyeroju, A.M., Malomo, A.O., Ogunseyinde, A.O., & Familusi, J.B. (2002). A comparison of visual function scores in hydrocephalic infants with and without lumbosacral myelomeningocele. *Eye, 16*, 739-743.

Simms, B. (1987). The route learning ability of young people with spina bifida and hydrocephalus and their able-bodied peers. *Zeitschrift für Kinderchirurgie, 42*, 53-56.

Souvignier, E. (2000). *Förderung räumlicher Fähigkeiten* [Encouragement of spatial abilties]. Münster: Waxmann.

Stanton, D., Wilson, P.N., & Foreman, N. (2002). Effects of early mobility on shortcut performance in a stimulated maze. *Behavioural Brain Research, 136*, 61-66.

Steggemann, Y., Engbert, K., & Weigelt, M. (2011). Selective effects of motor expertise in mental body rotation tasks: Comparing object-based and perspective transformations. *Brain and Cognition, 76*, 97-105.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donder´s method. *Acta Psychologica, 30*, 276-315

Stransky, D., Wilcox, L.M., & Dubrowski, A. (2010). Mental rotation: Cross-task training and generalization. *Journal of Experimental Psychology: Applied, 16,* 349-360.

Straßburg, H.-M. (2008a). Überwiegend motorische Entwicklungsstörungen. In H.-M. Straßburg, W. Dacheneder, & W. Kreß (Eds), *Entwicklungsstörungen bei Kindern* [Development disorder in children] (pp. 103-114). München: Urban & Fischer.

Straßburg, H.-M. (2008b). Ursachen und Formen mentaler Entwicklungsstörungen. In H.-M. Straßburg, W. Dacheneder, & W. Kreß (Eds), *Entwicklungsstörungen bei Kindern* [Development disorder in children] (pp. 114-161). München: Urban & Fischer.

Studer, T. (2011). *Motorik und Kognition. Eine experimentelle Untersuchung im Kindergartenalter.* [Motor skills and cognition. An experimental study in preschool-aged children] (Unpublished master´s thesis). Institut für Sport und Sportwissenschaft, Universität Basel, Basel.

Suchan, B., Botko, R., Gizewski, E., Forsting, M., & Daum, I. (2006). Neural substrates of manipulation in visuospatial working memory. *Neuroscience, 139*, 351-357.

Swain, M.A., Joy, P., Bakker, K., Shores, E.A., & West, C. (2009). Object-based visual processing in children with spina bifida and hydrocephalus: A cognitive neuropsychological analysis. *Journal of Neuropsychology, 3*, 229-244.

Uttal, D.H., Meadow, N.G., Tipton, E., Hand, L.L., Alden, A.R., Warren, C., & Newcombe, N.S. (2012). The malleability of spatial skills: A meta-anaylsis of training studies. *Psychological Bulletin*. Advance online publication. doi: 10.1037/a0028446

Vandenberg, S.G., & Kuse, A.R. (1978). Mental rotation. A group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*, 599-604.

Vernon, P.A. (1993). Der Zahlen-Verbindungstest and other trail-making correlate of general intelligence. *Personality and Individual Differences, 14*, 35-40.

Vidyasagar, T.R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences, 14,* 57-63.

von Moers, A. (1998). Äthiologie und Pathogenese. In: T. Michael, A. von Moers, & A.E. Strehl (Eds), *Spina bifida: Interdisziplinäre Diagnostik, Therapie und Beratung* [Spina bifida: interdisciplinary diagnostics, therapy and consulting] (pp. 1-3). Berlin: de Gruyter.

Voyer, D. (1995). Effects of training on laterality in a mental rotation task. *Brain and Cognition, 29*, 326-335.

Voyer, D., Voyer, S., & Bryden, M.P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*, 250-270.

Wassenberg, R., Feron, F.J.M., Kessels, A.G.H., Hendriksen, J.G.M., Kalff, A.C., Kroes, M., … Vles, J.S.H. (2005). Relation between cognitive and motor performance in 5- to 6-year-old children: Results from a large-scale cross-sectional study. *Child Development, 76*, 1092- 1103.

Weineck, J. (2010). *Optimales Training* [Optimal training]. Balingen: Spitta.

Wexler, M., Kosslyn, S.M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68*, 77-94.

Wiedenbauer, G., & Jansen-Osman, P. (2006). Spatial knowledge of children with spina bifida in a virtual large-scale space. *Brain and Cognition, 62,* 120-127.

Wiedenbauer, G., & Jansen-Osman, P. (2007). Mental rotation ability of children with spina bifida: What influence does manual rotation training have? *Developmental Neuropsychology, 32,* 809-824.

Wiedenbauer, G., & Jansen-Osmann, P. (2008). Manual training of mental rotation in children. *Learning and Instruction*, *18*, 30-41.

Wiedenbauer, G., Schmid, J., & Jansen-Osmann, P. (2007). Manual training of mental rotation. *European Journal of Cognitive Psychology, 19*, 17-36.

Wills, K.E., Holmbeck, G.N., Dillon, K., & McLone, D.G. (1990). Intelligence and achievement in children with myelomeningocele. *Journal of Pediatric Psychology, 15*, 161-176.

Wilson, P.H., Maruff, P., Butson, M., Williams, J., Lum, J., & Thomas, P.R. (2004). Internal representation of movement in children with developmental coordination disorder*:* a mental rotation task*. Developmental Medicine & Child Neurology, 46*, 754-759.

Witkin, H.A., Oltman, P.K., Raskin, E., & Karp, S.A. (1971). *Embedded Figure Test.* Palo Alto: Consulting Psychologist Press.

Wohlschläger, A. (2001). Mental object rotation and the planning of hand movements. *Perception & Psychophysics, 63*, 709-718.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 397-412*.*

Zacks, J. M. (2008). Neuroimaging studies of mental rotation: A meta-analysis and review. *Journal of Cognitive Neuroscience, 20*, 1-19.

Zimmer, H.D. (2008). Visual and spatial working memory: From boxes to networks. *Neuroscience and Behavioral Reviews, 32*, 1373-1395.

Zoelch, C., & Mähler, C. (2012). Zur Diagnostik von Arbeitsgedächtnisprozessen bei 3-bis 6-jährigen Kindergartenkindern. In: M. Hasselhorn, & C. Zoelch (Eds), *Funktionsdiagnostik des Arbeitsgedächtnisses* [Functional diagnostics of working memory processes] (pp. 159-181). Göttingen: Hogrefe.

Appendix

Appendix A: Overview of the stimuli used in Experiment 1 and 2.

Appendix B: Overview of the stimuli used in Experiment 3.

Appendix A

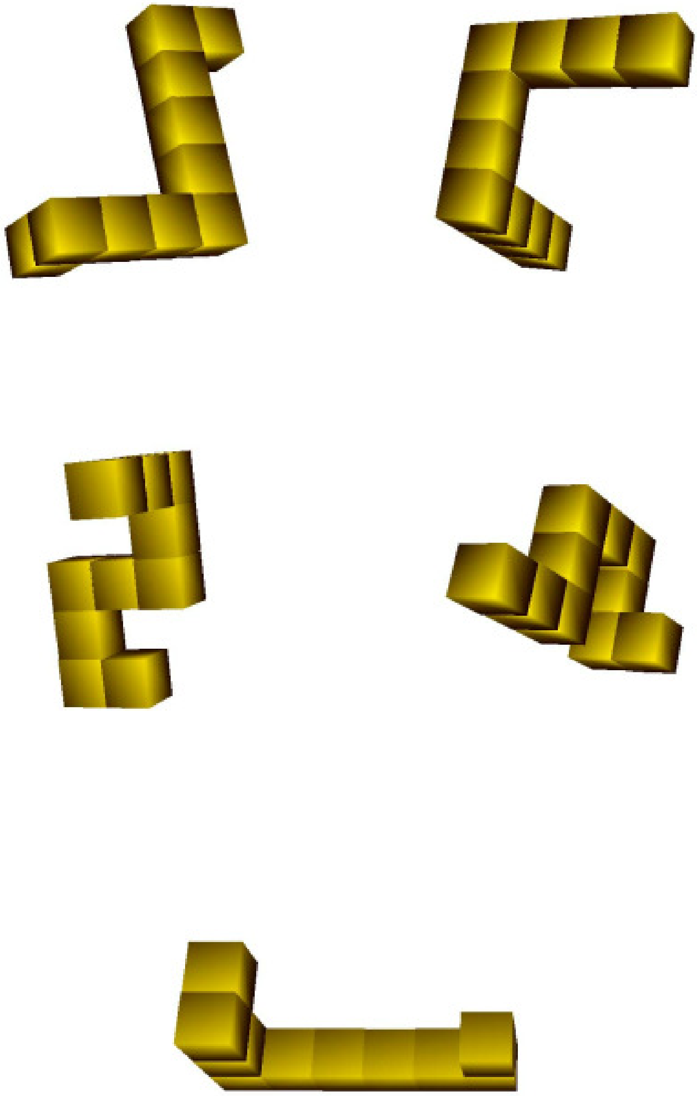

Figure A1: Cube figures that were applied in the chronometric mental rotation test (Experiment 1 and Experiment 2).

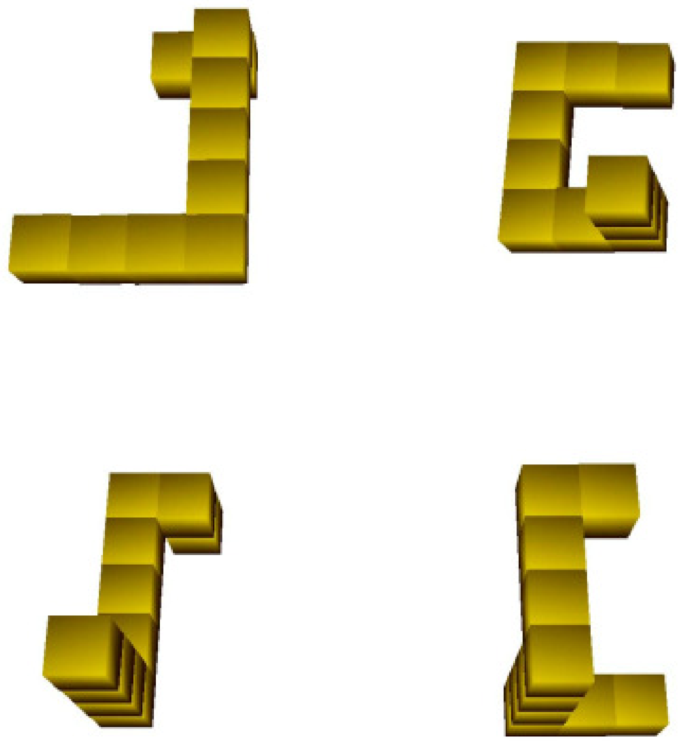

Figure A2: Cube figures that were applied in the chronometric mental rotation test (Experiment 1 and Experiment 2).

Appendix B

Figure B1: Animal stimuli used in the practice part of the chronometric mental rotation test in Experiment 3 (obtained from Rossion & Pourtois, 2004),

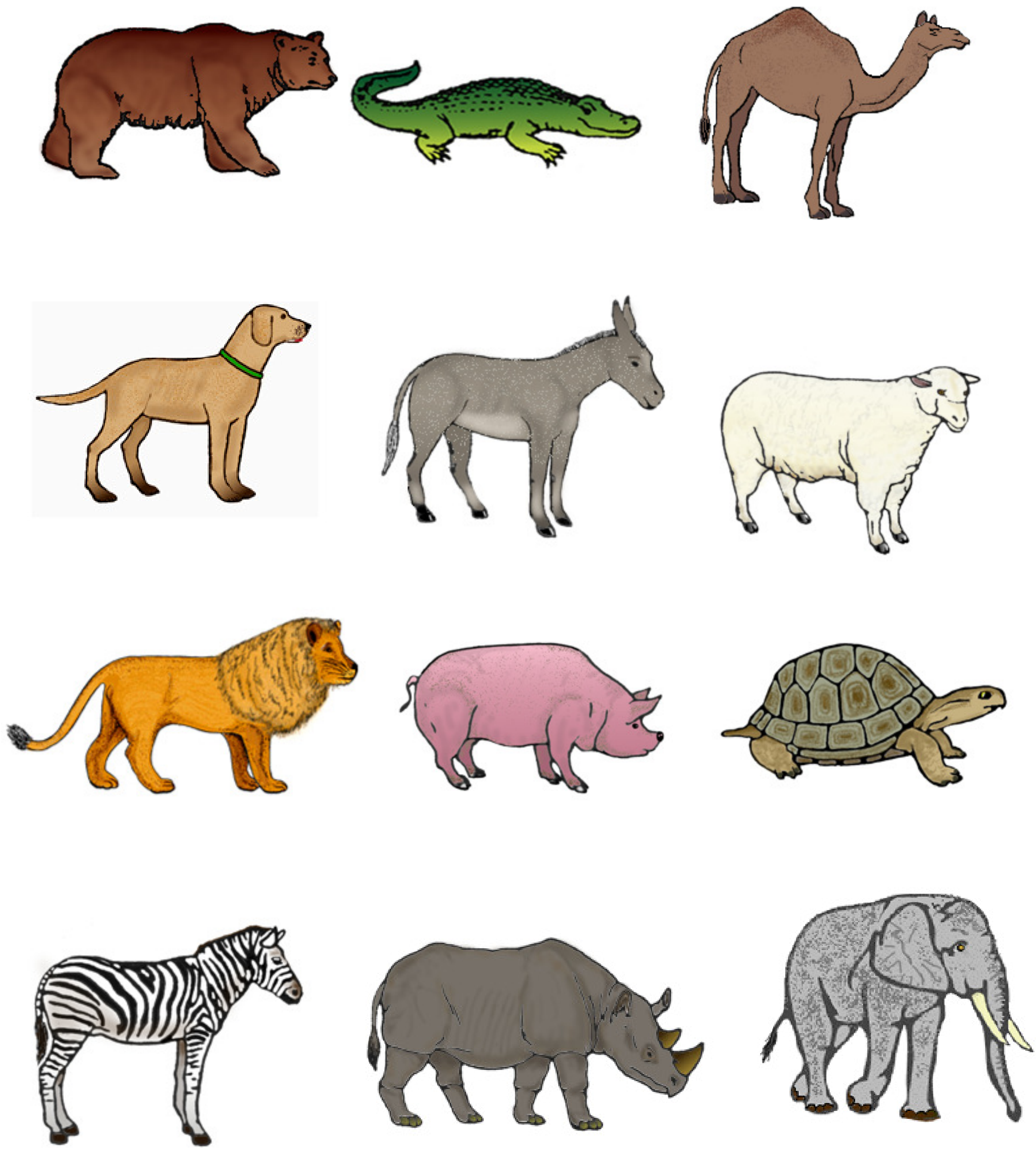

Figure B2: Anmial stimuli used in the experimental part of the chronometric mental rotation test in Experiment 3 (obtained from Rossion & Pourtois, 2004).