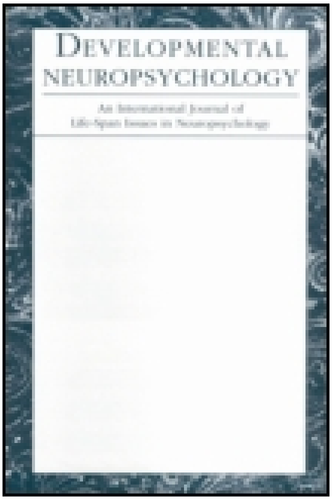

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Mental Rotation Ability of Children with Spina Bifida: What Influence Does Manual Rotation Training Have?

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Mental Rotation Ability of Children with Spina Bifida: What Influence Does Manual Rotation Training Have?

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We investigated the mental rotation ability of children with spina bifida, a malformation of the spinal cord due to a neural tube defect, and how it is influenced by a manual rotation training. In comparison to a healthy control group these children showed longer reaction times and a higher number of errors in a computer-based mental rotation test. Furthermore, a manual rotation training was applied. The spina bifida group benefited considerably from the manual rotation training. The training effect was not limited to stimuli learned in the training. While the children with spina bifida showed a lower speed of mental rotation than their healthy peers in the mental rotation pretest, the two groups did not differ in their mental rotation speed in the posttest.

In the classical paradigm of mental rotation established by Shepard and Metzler (1971), participants have to decide whether two block stimuli rotated in space are identical or mirror reversed. As reaction times increased linearly with increasing angular disparity between the stimuli it was assumed that participants use mental rotation to solve the task. While Shepard and Metzler investigated mental rotation in adults, the influence of angular disparity on reaction times in mental rotations tasks was also the subject of many studies in children. The linear function between reaction time and angular disparity could be shown in children as young as 5 years (e.g., Kosslyn, Margolis, Barrett, & Goldknopf, 1990; Marmor, 1975). Kail, Pellegrino, and Carter (1980) could show that the speed of mental rotation (defined as the inverse slope of the mental rotation function) increased with increasing age and seems to be a continuous age-related process (Kail, 1988): Similar to other speeded cognitive processes, mental rotation ability improves with increasing

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cognitive development. This raises the question whether a disruption of normal cognitive development affects mental rotation ability. Consequently, mental rotation was also the subject of studies with cognitive and physically impaired children, with mixed results. Uecker, Obrzut, and Nadel (1994) investigated mental rotation abilities in healthy, learning-disabled, and Down's syndrome children. Reaction times indicated that learning-disabled children were impaired relative to their healthy peers. Children with Down's syndrome were even slower and less accurate. Furthermore, they did not show a linear relationship between reaction times and angular disparity indicating that they were not employing mental rotation to solve the task. On the other hand, Zabalia and Mellier (1996) could not find performance differences in a mental rotation task between children with cerebral palsy and healthy children.

Mental rotation abilities have yet to be investigated systematically in children with spina bifida (myelomeningocele) who suffer from a malformation of the central nervous system due to a defect of the neural tube closure in early embryogenesis. Depending on the level of the spinal lesion, patients with spina bifida are more or less severely physically handicapped. Additionally, even though children with spina bifida show the full range of intellectual ability, the intelligence distribution is shifted towards the lower end of the spectrum by about a standard deviation (Casari & Fantino, 1998; Jacobs, Northam, & Anderson, 2001; Shaffer, Friedrich, Shurtleff, & Wolf, 1985; Tew, 1977; Wills, Holmbeck, Dillon, & McLone, 1990). In most of these studies, this reduction is mainly due to a diminished performance IQ which encompasses skills of logical and spatial thinking, processing speed, and visual perception and seems to implicate impairments of visual-spatial thinking (Shaffer et al., 1985). However, the difference between verbal and performance IQ seems to depend on the composition of the sample group (e.g. with regard to ethnicity, level of lesion; see Fletcher et al., 2005). The spatial deficits were investigated in more detail, for example by Sand, Taylor, Rawlings, and Chitnis (1973) who found children with spina bifida to be impaired in figure-ground perception. Additionally, Dennis, Fletcher, Rogers, Hetherington, and Francis (2002) could show that the impairments of children with spina bifida were much larger in action-based than in object-based tasks. While the children with spina bifida performed as well as the control group in face recognition tasks, they were particularly impaired in tasks requiring dorsal stream visual processing. Recently, it was shown that large-scale spatial behavior and knowledge are also affected in spina bifida children; they needed more trials to learn a route through a virtual environment, and recalled fewer landmarks than a control group of healthy children (Wiedenbauer & Jansen-Osmann, 2006).

Due to the reported visual-spatial impairments in children with spina bifida our main goal in this study was to investigate the mental rotation abilities. As mental rotation is of great importance to spatial abilities it is somewhat surprising that mental rotation abilities of children with spina bifida have never been investigated systematically before. When solving a mental rotation task, the dorsal processing stream is activated (see e.g., Podzebenko, Egan, & Watson, 2002). Therefore, according to the study by Dennis et al. (2002), it can be assumed that children with spina bifida are severely impaired in their mental rotation abilities. A second goal of our study was to improve these abilities by means of a manual rotation training. So far, training of mental rotation has only rarely been examined in studies with children. The effects of extended practice of mental rotation in 11-year-olds was studied by Kail and Park (1990). After working on more than 3,000 trials of mental rotation of four alphanumeric symbols, the children's mental rotation speed of those symbols was about six times higher than in the pretest (compare also Kail, 1986). This training effect was, however, restricted to the previously learned symbols, as the authors did not find a transfer effect to symbols which were not presented during training. The improvement of mental rotation in children as well as in adults (see e.g., Heil, Rösler, Link, & Bajric, 1998; Jolicoeur, 1985; Tarr & Pinker, 1989) might be due to the retrieval of stored stimulus representations.

Still it is essential that the rotation process itself is trained—especially in children with impaired visual-spatial abilities. We hypothesize that the appropriate means to train mental rotation could be *manual* rotation since they share the same underlying processes (Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). In neuro-imaging studies motor and premotor areas which are involved in the execution of movements were also found to be activated during mental rotation (e.g. Barnes et al., 2000; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Richter et al., 2000; Wraga, Thompson, Alpert, & Kosslyn, 2003). The manual training used in this study was previously evaluated with healthy children at the age of ten and eleven (see Wiedenbauer & Jansen-Osmann, in press): In comparison to a non-trained control group, the performance of the training group in a computer-based mental rotation test improved as a result of the manual rotation training. The resulting training effect was not restricted to drawings, which were presented in the previous learning phase. Since the results of the manual training in healthy children were promising, the next step was to apply the training to children with spina bifida, who suffer from an extensive visual-spatial deficit (see above). While these children show deficits in their spatial abilities, they are not impaired in learning (manual) motor skills (e.g., Colvin, Yeates, Enrile, & Coury, 2003; Edelstein et al., 2004). Thus a training tool, which improves spatial skills by requiring the execution of a manual task, should be effective. Due to this earlier successful implementation of the manual training and rareness of spina bifida, we abstain from choosing a control group of children with spina bifida playing the non-spatial computer game. Previous studies indicated that especially participants with initially poor spatial skills can benefit from a computer-based training (Rizzo et al., 2001; Saccuzzo, Craig, Johnson, & Larson, 1996) and showed the effectiveness of employing computer-based environments when training children with disabilities (McComas, Pivik, & Laflamme, 1998).

To sum up, we assume that children with spina bifida show impaired mental rotation abilities. To measure the mental rotation ability we used a computer-based mental rotation test, which records reaction times and errors. To analyze the reaction times in more detail, regression lines between angular disparity and reaction times were computed. Cooper and Shepard (1973) assumed that reaction times in a mental rotation task are composed of the time needed for the following processing stages: stimulus encoding, mental rotation of the stimuli, comparison of the stimuli, and motor response. While the slope of the regression lines indicates the speed of the mental rotation process itself, the axis intercept is not influenced by the angular disparity and is thus determined by the other processes (encoding, comparison, and motor response). Additionally, the fit of the regression lines (R^2) indicates how successful participants are in solving the task by mental rotation. Furthermore, we hypothesized that children with spina bifida will benefit considerably from manual training and that the potential training effects are not restricted to previously learned objects.

METHOD

Participants

Nineteen children with spina bifida and 19 healthy control children took part in the study. Spina bifida children were recruited by means of an advertisement in the journal of the *German Society of Spina bifida and Hydrocephalus*. Children of the control group were recruited in schools in and around Düsseldorf. All children in the spina bifida group had myelomeningocele and all but one child suffered from a shunted hydrocephalus. No child suffered from uncontrolled epilepsy, primary sensory loss, behavioral disorders, or motor impairments in the upper limbs. The location of the lesion was sacral in five, lumbal in ten, and thorocal in four children. The vision of all subjects was corrected to 20/20. Prior to testing, all parents gave their informed written consent for their children to take part in the study. The ethics committee of the German Psychological Society approved of the whole research project and the experimental procedure.

Three children with spina bifida were dismissed due to an overall error rate of above 40% in the mental rotation test. To form two comparable groups, 16 healthy children were matched according to sex, age, and verbal IQ (as measured by the German version of the WISC-III) with the remaining 16 children with spina bifida. Consequently, the two groups did not differ in their verbal IQ (spina bifida M = 97.88, SD = 12.74; control M = 102.31, SD = 11.82; $F(1,30) = 1.04$, $p = .32$, $\eta^2 = .03$) but did differ in their performance IQ (spina bifida M = 74.13, SD = 10.63; control M = 97.56, SD = 10.96; $F(1,30) = 37.69$, $p < .001$, $\eta^2 = .56$) as well as in their mean general IQ (spina bifida M = 84.94, $S.D$ = 10.05; control M = 100.12,

$SD = 10.22$; $F(1,30) = 17.97$, $p < .001$, $\eta^2 = .38$). Each group was composed of five boys and eleven girls with a mean age of 11.41 years ($SD = 1.67$; range 8–14 years) for the spina bifida group and 11.72 years ($SD = 1.75$; range 8–14 years) for the control group.

Materials and Design

The experiment was conducted on a Centrino laptop with a nVidia Geforce Go5200 graphic-card. The stimuli were projected onto the 15-inch flat-screen monitor of the laptop using the software 3D GameStudio A6. The distance between the monitor and the child was approximately 0.4 meters. Input devices were a two-button mouse and a Microsoft sidewinder precision joystick.

Mental rotation (MROT) pretest. In the MROT the children's task was to decide as quickly as possible whether two presented stimuli were identical or mirror images of each other while keeping errors to a minimum. The experimental stimuli consisted of colored drawings of six different animals (see Table 1 for the complete list of drawings). The pictures were taken from the colored set of the Snodgrass and Vanderwart pictures (Rossion & Pourtois, 2004; Snodgrass & Vanderwart, 1980) and were presented in front of a black background. On a given trial an animal was presented twice: An upright standard drawing was presented on the left side, a comparison drawing, which was rotated in the picture plane and either identical ("same" trials) or, in half of the trials, mirror reversed ("different" trials) was presented on the right side. Half of the standard drawings were presented facing to the left, the other half facing to the right. The angular disparity between the two figures was either 22.5°, 67.5°, 112.5°, or 157.5° clockwise as well as counter clockwise (i.e., 202.5°, 247.5°, 292.5°, or 337.5°). In each of the eight angular disparities, each pair of drawings was presented twice (once in a "same" and once in a "different" trial) which resulted in a total of 96 trials. Each trial started with a 500 msec presentation of a grey 5 mm fixation square followed by the two stimuli prompting the children to answer by pressing either the left mouse button marked in green ('same') or the right button marked in red ('different').

TABLE 1
Names of the Drawings Used in the MROT Pre- and Posttest and the Manual Rotation Training

	Drawings
MROT pretest	Elephant; Fox; Alligator; Cow; Leopard; Horse
Manual rotation training	Bear; Donkey; Dog; Pig; Tiger; Goat; Monkey; Bunny; Cat; Mouse; Turtle; Sea lion
MROT posttest	Bear; Donkey; Dog; Pig; Tiger; Goat; Camel; Lion; Rhinoceros; Deer; Sheep; Racoon

MROT posttest. A parallel version of the MROT was developed and used as posttest. The stimuli were presented in the same angular disparities as in the pretest. Stimuli were 12 drawings of animals, which were different from those used in the MROT pretest (see Table 1). This resulted in a total of 192 trials (i.e., twice the number of the MROT pretest trials). Note that none of the drawings presented in the pretest was used in the posttest.

Manual rotation training. As in the MROT a standard drawing was presented on the left side and a comparison drawing on the right side. The children's task was to manually rotate the comparison drawing in the picture plane into the orientation of the standard drawing. The 12 colored drawings of animals used in the training were taken from the same picture set as described above. To study object specific training effects, 6 of these drawings were later presented in the MROT posttest (see Table 1). This resulted in 6 "old" and 6 "new" figures in the MROT posttest.

Standard and comparison figures were always identical and only differed in their angular disparity in the picture plane. The angular disparities between the two presented figures were the same as in the MROT. Each comparison drawing was presented in each of the eight angular disparities. Since each trial was presented twice (but never consecutively) the training consisted of 192 trials.

Input device for rotating the comparison drawing was a joystick embedded in a card-board-box. This allowed for grasping the joystick as one would do when rotating a real object in the picture plane. When the joystick was turned right/left, the drawing rotated in the corresponding direction.

Procedure

The experimental sessions lasted for about 60 min. Each child was tested individually in their home in a silent room. All children were familiarized with the MROT in 24 practice trials. In this familiarization phase, a "correct"/"false" feedback for each trial was given. None of the drawings used here were presented in the following experimental phase of the MROT. After a 5-min break following the pretest, all children had to complete the manual rotation training. They were shown how to handle the joystick and were instructed to rotate the comparison drawing into the spatial orientation of the standard drawing and then to press the "fire button" of the joystick. If the spatial orientation of the standard and the comparison drawing differed by more than 15° to the right or to the left, the trial was registered as an error and the word "false" was presented in red letters. The trainings phase lasted for about 24 min. After the children had completed the manual training they had a 5-min break and afterwards had to perform the MROT posttest.

Dependent Variables and Statistical Analysis

Dependent variables were reaction time (RT) and number of errors. Within each angular disparity (22.5°, 67.5°, 112.5°, and 157.5°) the average RT in msecs for each child was computed only for correct answers in "same" trials (see Shepard & Metzler, 1971). Separately for each angular disparity and each child, RTs shorter than 500 msec and longer than two standard deviations above the mean were defined as outliers and therefore discarded. The mean number of errors (for both "same" and "different" trials) was computed over all angular disparities as well as separately for each angular disparity.

Baseline mental rotation ability. The MROT pretest data were analyzed to assess the mental rotation ability. An analysis of variance was computed for RT and mean number of errors; angular disparity was defined as a within-subject factor and group (spina bifida vs. control group) was defined as a between-subject factor. Furthermore, regression lines (least squares lines) between angular disparities and RTs were computed separately for each child. The fit of the regression lines (R^2), the slopes, and the intercepts were averaged across the children. An analysis of variance was computed including the averaged R^2, slope, and intercept as dependent variables and group as a between-subject factor.

Training effects. Separately for each angular disparity, difference scores between pretest and posttest were computed for RTs and mean number of errors (to account for the different number of trials only half of the errors in the posttest were subtracted from the number of errors in the pretest). To study training effects these difference scores were compared between the spina bifida and the control group. To analyze object specificity, we differentiated between trials with items that were trained in the manual rotation training ("old") and trials with untrained items ("new"). An analysis of variance was computed; angular disparity (22.5°, 67.5°, 112.5°, 157.5°) and item type ("old" vs. "new") were defined as within-subject factors, group (spina bifida vs. control group) was defined as a between-subject factor.

Furthermore, regression lines (least square lines) between angular disparities and RTs for the posttest were computed for each child. An analysis of variance was computed with the averaged R^2, slope, and intercept in the posttest as dependent variables and group as a between-subject factor.

Manual rotation behavior. Manual rotation time and number of errors in the manual rotation training were recorded. An error was registered if the spatial orientation of the standard and the comparison drawing differed by more than 15° to the right or to the left. Rotation time dependent on the angular disparity was analyzed only for correct responses. Within each angular disparity and separately for each participant, rotation times more than two standard deviations above the mean were defined as outliers and therefore discarded. The number of errors for each angular disparity and each child was determined. An analysis of variance was computed for rotation times and the mean numbers of errors; angular disparity (22.5°, 67.5°, 112.5°, 157.5°) was defined as a within-subject factor and group (spina bifida vs. control group) as a between-subject factor. Furthermore, regression lines (least square lines) between angular disparities and rotation times were computed separately for each participant. The fit of the regression lines (R^2), the slopes, and the intercepts were averaged across the children and an analysis of variance was computed with group as a between-subject factor.

Relation of mental and manual rotation. We computed the correlation between RT in the MROT and rotation time in the manual rotation training separately for the spina bifida and the control group. Furthermore, the slopes and intercepts of the MROT and the manual rotation training were correlated for each group.

RESULTS

Baseline mental rotation ability. Group had a significant effect on the RT in the MROT pretest, $F(1,30) = 20.78$, $p < .001$, $\eta^2 = .41$, and there was a significant effect of angular disparity, $F(3,90) = 67.32$, $p < .001$, $\eta^2 = .69$. Repeated contrasts revealed significant differences between all four angular disparities with higher RTs for higher angular disparities. Furthermore, there was a significant interaction between group and angular disparity, $F(3,90) = 3.9$, $p < .05$, $\eta^2 = .16$. Children with spina bifida were slower than the control group (see Table 2) and the difference between the smallest and the largest angular disparity was higher for the spina bifida group than for the control group. The averaged R^2 of the computed regression lines was .84, the slope was 10.3 msec/degree (97.1 degree/s), and the axis intercept was 1259.33 msec. The two groups differed in the slope (spina bifida: 12.73; controls: 7.86; $F(1,30) = 5.89$, $p < .05$, $\eta^2 = .16$), and the axis intercept (spina bifida: 1469.35; controls: 1049.32; $F(1,30) = 8.9$, $p < .05$, $\eta^2 = .23$), but not in the R^2 (spina bifida: .79; controls: .89; $F(1,30) = 2.4$, $p = .13$, $\eta^2 = .07$).

The overall error rate in the MROT was 11.26%. The mean number of errors for the spina bifida group was 2.13 ($SE = 0.35$) at the angular disparity of 22.5°, 2.88 ($SE = 0.63$) at 67.5°, 3.44 ($SE = 0.85$) at 112.5°, and 7.56 ($SE = 1.65$) at 157.5°. The mean number of errors for the control group was 0.63 ($SE = 0.23$) at 22.5°, 0.63 ($SE = 0.22$) at 67.5°, 1.88 ($SE = 0.42$) at 112.5°, and 2.5 ($SE = 0.65$) at 157.5°. The two groups differed significantly in their mean number of errors, $F(1,30) = 12.92$, $p = .001$, $\eta^2 = .3$. Angular disparity had a significant effect on the mean number of errors, $F(3,90) = 12.48$, $p < .001$, $\eta^2 = .29$. Repeated contrasts revealed significant differences between the three highest angular disparities with

TABLE 2
Mean Reaction Times and Reaction Time Differences for the Spina Bifida and the Control Group Against the Angular Disparity (Standard Errors in Parentheses)

		Angular Disparity			
		22.5°	*67.5°*	*112.5°*	*157.5°*
MROT pretest	Spina bifida	1863.81 (98.61)	2229.81 (161.96)	2774.94 (202.08)	3591.58 (285.98)
	Control group	1275.98 (71.53)	1534.65 (114.78)	1875.11 (102.83)	2341.73 (140.57)
MROT posttest	Spina bifida	1625.45 (104.32)	1793.17 (101.17)	2111.88 (111.54)	2463.06 (128.09)
	Control group	1142.54 (52.69)	1280.79 (51.68)	1573.22 (87.4)	1850.07 (89.22)
Reaction time difference*	Spina bifida	–238.36 (59.19)	–436.64 (121.44)	–664.31 (146.95)	–1128.52 (247.14)
	Control group	–133.43 (59.47)	–253.85 (90.87)	–301.89 (100.87)	–491.65 (153.18)

*Negativity indicates faster reaction times in the posttest.

increasing number of errors for increasing angular disparities. There was no significant interaction between group and angular disparity, $F(3,90) = 3.27$, $p = .06$, $\eta^2 = .1$.

Training effects (RT). As illustrated in Table 2, both groups showed shorter reaction times in the post- than in the pretest. The RT difference scores between the pre- and the posttest are also shown in Table 2. Group had a significant effect on the RT difference scores, $F(1,30) = 4.64$, $p < .05$, $\eta^2 = .13$. The RT difference scores for the children with spina bifida were much larger than those of the control group. Furthermore, angular disparity had a significant effect, $F(3,90) = 10.97$, $p < .001$, $\eta^2 = .27$. Repeated contrasts revealed significant differences between 22.5 and 67.5° and between 112.5 and 157.5°. There was no difference between "old" and "new" items in RT difference scores, $F(1,30) = 0.36$, $p = .55$, $\eta^2 = .01$. Furthermore, no significant interactions were found.

Regarding the parameters of the regression lines in the posttest, the averaged R^2 was .87, the slope was 5.83 msec/degree (171.53 degree/s), and the axis intercept was 1205.37 msec. The two groups differed neither in the R^2 (spina bifida: .83; controls: .90; $F(1,30) = 2.28$, $p = .14$, $\eta^2 = .07$) nor in the slope (spina bifida: 6.29; controls: 5.37; $F(1,30) = 1.56$, $p = .22$, $\eta^2 = .05$). The children with spina bifida, however, had higher axis intercepts (1432.08 msec) than their healthy peers (978.65 msec), $F(1,30) = 17.97$, $p < .001$, $\eta^2 = .38$.

Training effects (errors). Difference scores (pre vs. post) of mean number of errors for the children with spina bifida were –0.75 (*SE* = 0.53) at 22.5°, – 1.66 (*SE* = 0.7) at 67.5°, –2.0 (*SE* = 0.77) at 112.5°, and –3.62 (*SE* = 1.23) at 157.5°. For the control group, difference scores were –0.22 (*SE* = 0.32) at 22.5°, 0.19 (*SE* = 0.22) at 67.5°, –1.28 (*SE* = 0.36) at 112.5°, and –1.66 (*SE* = 0.68) at 157.5°. Note that negativity indicates fewer errors in the posttest. These difference scores differed between the groups, $F(1,30) = 5.0$, $p < .05$, $\eta^2 = .14$. While both groups made fewer errors in the posttest than in the pretest, children in the spina bifida group had higher difference scores than their healthy peers indicating a larger training effect. Furthermore, angular disparity had a significant effect, $F(3,90) = 4.95$, $p < .05$, $\eta^2 = .14$. Repeated contrasts revealed that this effect was restricted to the comparison between 67.5° and 112.5°. There were no other significant effects or interactions for error difference scores.

Manual rotation behavior. The two groups differed significantly in the manual rotation time, $F(1,30) = 12.46$, $p < .001$, $\eta^2 = .29$. Children with spina bifida were slower than their healthy controls. Furthermore, angular disparity had a significant effect on rotation time in the manual training, $F(3,90) = 634.91$, $p < .001$, $\eta^2 = .96$. Repeated contrasts revealed significant differences between all angular disparities (see Table 3). There was no interaction between group and angular disparity, $F(3,90) = 0.63$, $p = .57$, $\eta^2 = .02$. Rotation time increased linearly with increasing angular disparity, the averaged R^2 for the regression lines was .98. The slope averaged across participants was 21.4 mecs/degree (46.73 degree/s) and the axis intercept was 2596.26 msec. Children with spina bifida had lower axis intercepts than the controls (spina bifida: 3067.72; controls: 2124.79; $F(1,30) = 10.14$, $p < .05$, $\eta^2 = .25$). There were no differences in the R^2 (spina bifida: .98; controls: .98; $F(1,30) = 0.004$, $p = .95$, $\eta^2 < .01$) and the slope (spina bifida: 21.81; controls: 20.99; $F(1,30) = 0.41$, $p = .53$, $\eta^2 = .01$).

The overall error rate in the manual rotation training was 2.23%. The mean number of errors for the spina bifida group was 0.25 (*SE* = 0.11) at 22.5°, 1.25 (*SE* = 0.38) at 67.5°, 0.81 (*SE* = 0.32) at 112.5°, and 0.94 (*SE* = 0.28) at 157.5°. The mean number of errors for the control group was 0.88 (*SE* = 0.33) at 22.5°, 1.88

TABLE 3
Rotation Times in the Manual Training for the Spina Bifida and the Control Group Against the Angular Disparity (Standard Errors in Parentheses)

	Angular Disparity			
	22.5°	*67.5°*	*112.5°*	*157.5°*
Spina bifida	3614.61 (212.69)	4486.29 (205.32)	5461.46 (198.08)	6561.73 (231.87)
Control group	2631.55 (197.91)	3476.21 (208.73)	4514.76 (234.71)	5434.43 (207.16)

(SE = 0.38) at 67.5°, 1.0 (SE = 0.37) at 112.5°, and 1.56 (SE = 0.43) at 157.5°. There was no effect of group, $F(1,30) = 2.21$, $p = .15$, $\eta^2 = .07$. Angular disparity had a significant effect on the mean number of errors, $F(3,90) = 5.31$, $p < .05$, $\eta^2 = .15$. Repeated contrasts revealed significant differences between the three smallest angular disparities. There was no interaction between group and angular disparity, $F(3,90) = 0.34$, $p = .78$, $\eta^2 = .01$.

Relation of mental and manual rotation. The RT in the pretest correlated significantly with the rotation time in the manual training for the children with spina bifida ($r = .55$, $p < .05$) but not for the control group ($r = .39$, $p = .14$). The same was true for the correlation between the RT in the posttest and the rotation time (spina bifida: $r = .68$, $p < .001$; control group: $r = .39$, $p = .14$). The correlation of the parameters of the regression lines revealed that the parallels between the mental and manual rotation in the spina bifida group seemed to rely on the axis intercepts: the axis intercept of the manual rotation correlated with the axis intercept in the MROT pretest ($r = .57$, $p < .05$) and posttest ($r = .65$, $p < .05$). There were no correlations regarding the parameters of the regression lines for the control group.

DISCUSSION

In a computer-based mental rotation test we found children with spina bifida to be impaired in their mental rotation ability relative to matched healthy controls. Furthermore, we applied manual rotation training, which improved considerably the mental rotation ability of children with spina bifida. It could be shown that spatial processing deficits are malleable and can be changed. The training effect for both, the children with spina bifida and the healthy children was not limited to items, which were learned, in the previous training.

Like numerous other studies on mental rotation in children we used two-dimensional drawings to investigate mental rotation abilities in 8- to 14-year-olds (e.g., Estes, 1998; Marmor, 1975, 1977; Roberts & Bell, 2002). Our results show that both, healthy children and those suffering from spina bifida solved the task by employing mental rotation (see Shepard & Metzler, 1971): The larger the angular disparities between the two stimuli the longer were the reaction times. Children with spina bifida were, however, slower to complete the task than their healthy peers. Analyzing the reaction times in detail, we found that the two groups differed in the slope and the axis intercept of the regression lines between angular disparity and reaction times. While the slope of the regression lines indicates the speed of the mental rotation process itself, the axis intercept is determined by other processes like encoding, comparison, and motor response (Cooper & Shepard, 1973). Children with spina bifida seemed to be impaired in all of these processes. The two groups did, however, not differ in the fit of the regression lines; both groups showed a linear relation between angular disparities and reaction times which further illustrates the children's ability to successfully apply mental rotation to the given task. The speed of mental rotation for the children with spina bifida was 78.6 °/s and thus slower than that of the healthy group in our study (127.2 °/s). This clearly indicates that children with spina bifida show an impaired speed of cognitive processing.

In the manual rotation task, which served as the training, children with spina bifida showed slower rotation times than their healthy peers. The detailed analysis of the rotation times by computing regression lines revealed that the two groups differed only in the intercept data. The speed of the manual rotation process itself was thus the same for both groups, which indicates that the slower rotation times for the disabled children were not caused by motor deficits but rather by impaired mental processes like encoding and comparing the stimuli. This is in line with studies which could show that motor learning is not impaired in children with spina bifida (Colvin et al., 2003; Edelstein et al., 2004). Furthermore, it could be argued that children with spina bifida solve mental rotation tasks by employing motor strategies since their performance in the mental rotation task as measured by reaction times correlated significantly with the performance in the manual task.

According to the mental rotation posttest, the computer-based manual rotation training had an effect on the mental rotation abilities. Note that we did not examine a non training group due to the prior successful evaluation of the manual training (Wiedenbauer & Jansen-Osmann, in press) and the difficulty to find children with spina bifida for an additional group. Thus we concentrated on the differential effect the training had on the spina bifida and the control group. Descriptively, both the spina bifida and the control group improved their mental rotation abilities. We could show, however, that especially children with spina bifida benefited from the manual training. The reaction time difference scores between the pre- and the post-test were nearly twice as high for the spina bifida group indicating a drastic decrease of reaction times. This result is in accordance with one position within the cognitive training literature that postulates that particularly subjects with poor mental rotation abilities can benefit from a rotation training (Rizzo et al., 2001; Sacuzzo et al., 1996). However, since the assignment to the groups was not random and since we did not have a non training group we can not exclude a regression toward the mean. In this case an improvement from the pre- to the posttest would have been observable without a true change in performance. Thus it is possible that the differential performance between the groups would not be replicated with random assignment. Further studies should investigate the effect of training by random assignment within a group of children with spina bifida.

While the slope of the regression lines differed between the two groups in the pretest this was not the case in the posttest. This indicates that, as a result of the training, the spina bifida group was able to perform the mental rotation itself in the posttest as quickly as the control group. Thus it seems that indeed the mental rotation process and not other processes like encoding or comparison were improved.

Regarding the number of errors, both groups were more accurate in the posttest than in the pretest. The difference score for the number of errors was significantly higher for the spina bifida group.

Lastly we could show that the manual training was not object specific. In the mental rotation posttest we differentiated between figures presented in the previous training and 'new' ones. The training effect we found was not limited to learned figures, which is in line with our initial assumption. Thus we seem to have developed an effective training program, which improves the mental rotation process itself and does not merely promote the retrieval of stimulus representations that were encoded in the training phase. However, based on the present study it is not possible to decide whether the training effect is due to the manual component or due to the visualization of the rotation process. It would be of great interest to investigate the critical components of the training and their relative contributions to the effectiveness in further studies with spina bifida patients.

To summarize, this was the first study, which systematically investigated the mental rotation abilities of children with spina bifida. It was shown that children with spina bifida use mental rotation when deciding whether two stimuli are identical or mirror reversed. The speeds of mental rotation, as well as the intercept data of the mental rotation function were, however, lower than that of their matched healthy peers. Children with spina bifida benefited considerably from the manual rotation training we developed. For both groups, the training effect seemed to be based on the improvement of the mental rotation process itself. Subsequent to the training, the children with spina bifida showed the same speed of mental rotation as the control group did. Thus spatial processing deficits assessed by a mental rotation task seem to be malleable. Due to these results it seems promising to validate the benefit of the training program with other populations of children with visual-spatial deficits.

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