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Spatial knowledge of children with spina bifida in a virtual large-scale space ☆

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Abstract

The spatial knowledge of 18 children with spina bifida and 18 healthy control children (matched according to sex, age, and verbal IQ) was investigated in a computer-simulated environment. All children had to learn a route through a virtual floor system containing 18 landmarks. Controlling for cognitive abilities, the results revealed that children with spina bifida showed impaired route knowledge but not an impaired landmark knowledge. Thus the results suggest that children with spina bifida are not impaired in all large-scale abilities similarly. The impairments of the children with spina bifida are more accentuated in more behaviour based measurements, which indicates a relation to the reduced mobility of the children with spina bifida.

Keywords: Spatial cognition; Landmark and route knowledge; Children; Virtual environments; Spina bifida

1. Introduction

The main goal of the present study was to investigate the spatial knowledge of children with spina bifida in a large-scale environment, a topic which has not been investigated yet. Due to their neurological malformation we assumed that the spatial knowledge of children with spina bifida is retarded and that this is due to their reduced mobility. In the following we give an overview of (a) the development of spatial knowledge in healthy children, (b) the disease pattern of spina bifida with emphasis on the cognitive abilities, and (c) the methodological difficulties to investigate the spatial knowledge of these children until now. Finally, we define the goal and the realization of our study.

1.1. The development of spatial behaviour and knowledge in healthy children

Spatial knowledge acquired in a large-scale space, an environment which can not be surveyed from one single vantage point, can be divided into landmark knowledge (i.e. knowledge of certain objects in the environment), route or procedural knowledge (i.e. knowledge of routes between these objects), and survey knowledge (i.e. survey representations which entail spatial relations and metric information, see Golledge, 1987; Siegel & White, 1975; Thorndyke, 1981). The definitions of the term "landmark" thereby range from landmarks as reference points that determine the localization of other points in the environment (Sadalla, Burroughs, & Staplin, 1980) to landmarks as visual objects that are perceived and remembered (Presson & Montello, 1988). In studies with children toys are often used as landmarks (e.g. Cohen & Schuepfer, 1980). In a recent study, the neural representation of toys which were relevant for navigation was investigated with adults (Janzen & van Turennout, 2004). The results in a recognition test showed increased activity (a) in the right fusiform gyrus for

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navigation-relevant objects and (b) in the parahippocampal area for landmarks at decision-points, even for those which were not explicitly recognized.

Former studies have shown that even very young children (under 1 year) are already able to use landmark information (Newcombe & Huttenlocher, 2000). Significant developmental changes in spatial coding, reasoning, and spatial symbol systems, in fact, are not completed with infancy but continue through school-age (Allen, Kirasic, Siegel, & Herman, 1979; Newcombe & Huttenlocher, 2000). Some authors assume a development from landmark to route knowledge (e.g. Siegel & White, 1975). Cornell, Heth, and Broda (1989) provided evidence that proximal, near-by landmarks are important for younger and older children during navigation, while only older ones were able to use distant landmarks.

1.2. The disease pattern of spina bifida

Spina bifida (myelomeningocele) is a malformation of the central nervous system; more precisely it describes a defect of the neural tube closure in early embryogenesis. In 80% of the cases, spina bifida is coupled with hydrocephalus. Depending on the location of the defect, patients with spina bifida are more or less severely physically handicapped. Around 0.5 per 1000 live births in Central Europe suffer from spina bifida.

Children with spina bifida bear a higher risk of mental retardation. General intelligence quotients (IQ) between 80 and 92 were measured in several studies (Casari & Fantino, 1998; Jacobs, Northam, & Anderson, 2001; Shaffer, Friedrich, Shurtleff, & Wolf, 1985; Tew, 1977; Wills, Holmbeck, Dillon, & McLone, 1990). In most of these studies, a significant discrepancy between verbal IQ and performance IQ with higher scores on the former was found. The performance IQ is based on skills of logical and spatial thinking, processing speed, and visual perception. It is controversially discussed which part of the visual-spatial subcomponent of working memory is impaired to a higher degree, the visual or the spatial one (see Mammarella, Cornoldi, & Donadello, 2003). Studying the visual-spatial abilities in detail, hydrocephalic children with and without spina bifida showed large impairments, especially in tasks involving figure-ground perception (Miller & Sethi, 1971; Sand, Taylor, Rawlings, & Chitnis, 1973). On the other hand, Dennis, Fletcher, Rogers, Hetherington, and Francis (2002) compared the effect sizes for differences between children with spina bifida and control subjects in spatial tests. They showed that the impairments of children with spina bifida were much higher in action-based tasks (egocentric mental rotation, multistable figures, figure-ground perception, route planning etc.) than in object-based tasks (visual illusions, face recognition, object identification, line orientation). Moreover, the spina bifida group performed as well as the control group in a spatial memory task in which a sequence of positions had to be retained.

1.3. Difficulties in investigating spatial knowledge of children with spina bifida and new opportunities

Beside the observation that visual-spatial abilities are impaired in children with spina bifida, little is known about their spatial knowledge in a large-scale space which must be explored successively. To date, only one study exists which investigates the spatial knowledge of patients with spina bifida (Simms, 1987). Nine young adults with spina bifida and nine healthy controls were driven in a car through a traffic free road system and around a busy village centre and had to learn the driven routes. Afterwards the participants had to find the correct routes by directing the driver. Furthermore, they had to mark each route on a map and to draw a sketch map of the routes. The results revealed that the control subjects made significantly fewer errors than the patients with spina bifida in finding the correct route and had fewer difficulties to mark the routes on the map. Both groups had difficulties in drawing the sketch map. Additionally, the ability to acquire route knowledge correlated with performance in a picture reasoning task. Simms (1987) concluded that general environmental experience—e.g. the use of public transport and bicycles—is more important than perceptual skills in learning a route in a real life situation. Reduced mobility therefore seems to result in impaired route learning abilities of young adults.

Until now, no study with children with spina bifida exists which investigated the acquisition of spatial knowledge in a systematic manner. Most possibly, this absence is caused by the fact that in research on spatial abilities, spatial knowledge in large-scale spaces in general is still neglected (Hegarty & Waller, 2005; Quaiser-Pohl, Lehmann, & Eid, 2004). This might be due to methodological problems which are associated with the investigation of spatial knowledge in real and laboratory large-scale environments (Jansen-Osmann, 2006) concerning the well-known limitations of internal validity regarding real environments and the limitations of the ecological and external validity of laboratory settings. By creating three dimensional *virtual environments* e.g. on a monitor, the gap between the need to test children in environments permitting experimental control and those having some ecological validity can be bridged (Blades, 1997). Furthermore, continuous measurements during navigation are possible.

In studies with children, virtual environments are only rarely employed for disabled children (Foreman, Stanton, Wilson, & Duffy, 2003; Stanton, Wilson, & Foreman, 2002; Wilson, Foreman, Stanton, & Duffy, 2004). In the study of Stanton et al. (2002) unhindered and physically disabled teenagers had to learn a route in a computer-simulated maze. The results showed that physically disabled teenagers had more difficulties than their healthy peers to choose correct short-cuts. Furthermore, the performance of disabled participants whose mobility was impaired in early development was poorer than that of teenagers whose mobility deteriorated later in development. Deficits in the exploration of space in childhood, therefore, seem to result in

impairment of spatial knowledge later in life (see also Yan, Thomas, & Downing, 1998).

1.4. The goal of this study

The main goal of this study was to investigate the spatial knowledge of children with spina bifida. We gave a summary about the development of spatial knowledge in school-age children and pointed out the difficulties in the acquisition of spatial knowledge in young adults with spina bifida. Due to the accentuation of sensorimotor activities (Piaget & Inhelder, 1971), and locomotion (McComas, Dulberg, & Latter, 1997) as being important for spatial learning and due to neuroscience studies which emphasize the change of cortical plasticity after the training of juggling (Draganski et al., 2004), sports (Kramer, Bherer, Colcombe, Dong, & Greenough, 2004), or dance (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005), we hypothesize that children with spina bifida are retarded because of their reduced mobility.

To investigate the potential impairments of large-scale spatial abilities in children with spina bifida we chose a desktop virtual environment, which had already been successfully used in studies with adults (Jansen-Osmann, 2002) and children (Jansen-Osmann & Wiedenbauer, 2004b). These studies replicated a classical study of Cohen and Schuepfer (1980). In the study of Jansen-Osmann and Wiedenbauer (2004b), second graders, sixth graders, and adults learned a route through a virtual maze which contained landmarks—18 toy animals—with different functions (adjacent to a correct turnoff, to an incorrect turnoff, or not adjacent to a turnoff, see Fig. 2). After learning the route, participants had to find the same route in absence of the landmarks and additionally had to recall the landmarks in a recall test. While the age groups did not differ in the number of trials needed to learn the correct route (route knowledge), the second graders made more errors than sixth graders and adults in absence of the landmarks (route knowledge), and recalled fewer landmarks (landmark knowledge).

Since the experimental setting of Jansen-Osmann and Wiedenbauer (2004b) was successfully employed with young children, it was chosen to investigate the spatial knowledge of children with spina bifida. The same experimental setup including the same measurements for route (trials to learn a route, number of errors) and landmark knowledge (recall of landmarks names and correct positions) were chosen. Due to their mobility impairment we assume that children with spina bifida should show an impaired route learning performance when compared with healthy control children. Furthermore, their landmark knowledge might also be impaired.

2. Method

2.1. Participants

Eighteen children with spina bifida and 18 healthy control children participated in the study. They were matched pair wise according to sex, age, and verbal IQ (as measured by the German version of the WISC-III). Consequently, the two groups did not differ in their verbal IQ (spina bifida $M=98.44$, $SD=12.01$; controls $M=103.28$, $SD=9.94$; $F(1,34)=1.73$, $p=.2$, $\eta^2=.048$). The two groups differed, however, in their performance IQ (spina bifida $M=72.06$, $SD=12.28$; controls $M=100.06$, $SD=12.22$; $F(1,34)=47.02$, $p<.001$, $\eta^2=.58$) as well as in their general IQ (spina bifida: $M=84.2$, $SD=10.17$; controls: $M=101.72$, $SD=8.52$; $F(1,34)=31.33$, $p<.001$, $\eta^2=.49$). Each group comprise 6 boys and 12 girls with a mean age of 11.26 years ($SD=1.8$) for the spina bifida group and 11.67 years ($SD=1.8$) for the control group. 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 Duesseldorf. The parents of the children with spina bifida had to complete a questionnaire about the medical condition and the motor development in early childhood. The usually observed comorbidity with hydrocephalus existed in all but one child with spina bifida. All hydrocephalic children had been treated by a shunt. No child suffered from uncontrolled epilepsy, primary sensory loss, or other behavioural disorders. The location of the lesion was in lumbal regions in 10 of the children, and in sacral and thorocal regions, respectively, in four children. The mean age in which the children with spina bifida learned to walk—with our without orthopaedic help—was 29.11 months. 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 the whole research project and the experimental procedure.

2.2. Materials

The experiment was conducted in a virtual environment using the software 3D GameStudio A5 on a Centrino laptop with a nVidia Geforce Go5200 graphic-card. The virtual world was projected onto the 15-inch flat-screen monitor of the laptop. The distance between the monitor and the child was about 0.4 m. Participants explored the simulated maze by using a joystick. The rotation and translation settings of the joystick were fixed across all participants.

A view into the maze is presented in Fig. 1. The virtual maze consisted of six main corridors. From each main corridor three corridors branched off, two of which were dead ends (see Fig. 2). In the maze, only multiples of 90° turns existed and only one route led to the goal. To reach the goal, the correct sequence of turns was right, right, left, left, right, left (in total three times left and three times right). Since it was not possible to see whether a turnoff was a dead end while passing an intersection, the subjects were required to rotate the joystick into the direction of this route segment.

The maze contained 18 different virtual toy animals, which were located in various positions. In Fig. 2, "+" denotes a landmark adjacent to a correct turnoff (in line

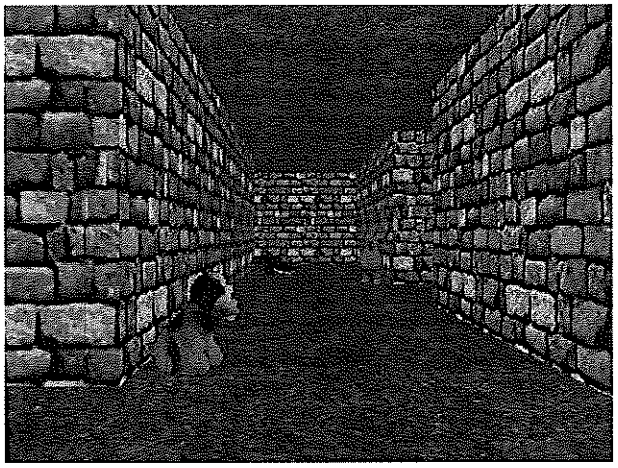

Fig. 1. A snap-shot into a corridor in the maze.

with the correct route to the goal),"−"a landmark adjacent to an incorrect turnoff (leading into a dead end), and "o" a landmark not adjacent to a turnoff. The maze itself was identical in all trials except for the presence of the landmarks: While the learning trials contained landmarks, the test and recall trials did not. The routes explored by the participants were automatically recorded.

2.3. Procedure

Children were tested individually in a laboratory at the Heinrich-Heine-University Düsseldorf. The experiment lasted approximately 30 min per participant. To control the influence of prior joystick experience, all subjects were familiarized with the use of the joystick in a non-experimental virtual world. To initiate a movement the joystick had to be pushed until dead stop. The velocity of the simulated movement through the maze was thus constant at about 0.9 m/s for all participants. Rotations were executed with 10°/s. As soon as participants were sufficiently familiar with the joystick, the experiment proper began. The four experimental phases succeeded in the following order:

Route knowledge

1. Learning phase 1: First, all children had to explore the maze until they reached the goal in four consecutive attempts without an error. The landmarks were present in the learning phase. The number of learning trials was recorded.
2. Test trial: Next, the children had to navigate correctly through the maze once while the virtual animals were absent. Errors on their way to the goal were recorded.
3. Learning phase 2: The children had to reach the goal in the presence of landmarks without an error in two consecutive trials. The number of trials was recorded.

Landmark knowledge

4. Recall test: To test their landmark knowledge, the children had to recall the identities and the locations of the virtual animals while they walked through the empty maze. The identities and locations were registered in an overview of the maze on a sheet of paper by the experimenter. The children had not been informed beforehand that they would have to recall the landmarks.

2.4. Experimental Design

Dependent variables were:

1. Route knowledge:
   (a) Number of trials needed in learning phase 1 until the four consecutive errorless criterion runs were completed.
   (b) Number of errors in the test trial. In accordance with the study of Cohen and Schuepfer (1980) and Jansen-Osmann and Wiedenbauer (2004b), an error was defined as walking or looking into a dead end. It was not considered an error when participants deviated slightly from the optimum path without leaving the corridor.

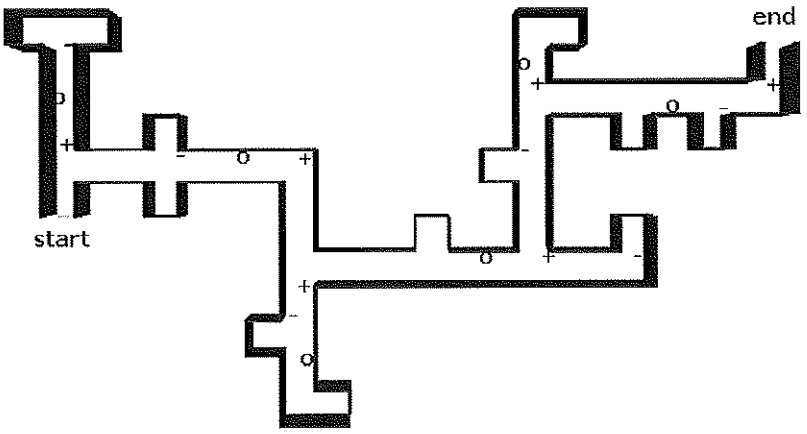

Fig. 2. An overview of the maze ("+" denotes a landmark adjacent to a correct turnoff, "−" denotes a landmark adjacent to an incorrect turnoff, "o" denotes a landmark not adjacent to a turnoff).

2. Landmark knowledge:
   (a) Number of recalled landmarks (recall of the identity of the animals irrespective of whether or not its correct location was recalled).
   (b) Number of recalled landmarks when the correct location was recalled as well.

Univariate analyses of variance were computed for learning trials and number of errors including the performance IQ as a covariate. Group (spina bifida vs. control group) served as a between subject factor. Furthermore, for number of recalled landmarks, a 2 (group) × 3 (type of landmark) analysis of variance was performed including the performance IQ as a covariate. Type of landmark (adjacent to a correct or an incorrect turnoff, and not adjacent to a turnoff) was defined as a within subject factor. Significance levels of all ANOVA results were corrected according to Greenhouse-Geisser to compensate for the non-sphericity of the data.

Additionally, we investigated the relationship between the age in which the children with spina bifida learned to walk and the measures of spatial knowledge. Therefore, a partial correlation between these variables was computed while controlling for the performance IQ.

3. Results

3.1. Route knowledge

3.1.1. Number of trials in learning phase 1

Group had a significant effect on the number of trials needed for initial learning of the correct route, $F(1,33)=4.30$, $p<.05$, $\eta^2=.12$. As illustrated in Fig. 3, children with spina bifida needed more trials to reach the learning criterion ($M=6.0$, $SE=0.65$) than the children in the control group ($M=2.9$, $SE=0.28$).

3.1.2. Number of errors in test trial

Fig. 3 shows the mean number of errors in the test trial. Again, there was a significant effect of group, $F(1,33)=4.86$, $p<.05$, $\eta^2=.13$. Children with spina bifida made more incorrect turns ($M=2.56$, $SE=0.57$) than the control children ($M=0.50$, $SE=0.16$).

All children were able to reach the criterion in the learning phase 2 without an error.

3.2. Landmark knowledge

The number of recalled landmark identities irrespective of whether or not participants correctly recalled the location was not significantly influenced by the factor group, $F(1,33)=2.10$, $p=.16$, $\eta^2=.06$. Children with spina bifida recalled 6.11 landmarks ($SE=0.66$), while the children of the control group recalled 8.78 landmarks ($SE=0.57$).

The analysis of the number of recalled landmarks on their correct locations revealed no significant effect of group, $F(1,33)=1.52$, $p=.23$, $\eta^2=.04$. Although children with spina bifida seemed to recall fewer landmarks on correct locations ($M=5.0$, $SE=0.7$) than controls ($M=7.8$, $SE=0.59$), this difference was not significant. There was an effect of type of landmark, $F(2,66)=7.27$, $p<.05$, $\eta^2=.16$. Helmert contrasts revealed that, in general, children recalled more landmarks adjacent to a correct turnoff ($M=4.72$, $SE=0.24$) than landmarks adjacent to an incorrect turnoff ($M=0.67$, $SE=0.16$) or not adjacent to a turnoff ($M=1.02$, $SE=0.21$). As can be seen in Fig. 4, there was sno interaction between group and type of landmark, $F(2,66)=0.76$, $p=.45$, $\eta^2=.02$.

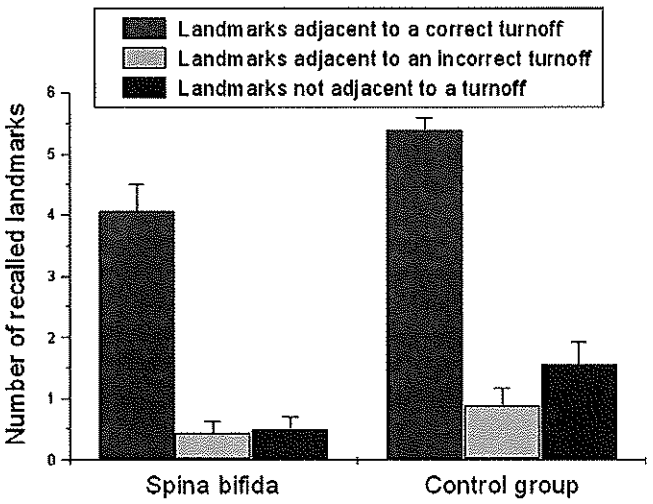

Fig. 4. Mean number of landmarks recalled at correct locations for the children with spina bifida and the control children dependent upon the type of landmarks. Error bars indicate standard errors.

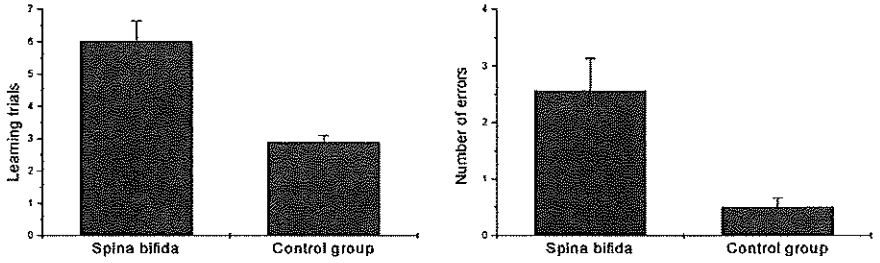

Fig. 3. Mean number of learning trials in learning phase 1 for the children with spina bifida and the control children (left panel). Mean number of errors in the test trial for the children with spina bifida and the control children (right panel). Error bars indicate standard errors.

3.3. Correlation between the age children with spina bifida learned to walk and spatial knowledge

The age in which the children with spina bifida learned to walk was highly correlated with the number of learning trials ($r = .65$; $p < .05$), but not so with the errors in the test trial ($r = .21$; $p = .48$) or the recalled landmarks ($r = -.13$; $p = .68$).

4. Discussion

In the present study, the spatial knowledge of children with spina bifida and their healthy controls in a large-scale environment was systematically investigated. The results are straightforward: First, in both measurements concerning route knowledge, children with spina bifida showed a reduced performance compared to the healthy children in the control group although performance IQ was controlled. Children with spina bifida had to walk more often through the maze to learn the correct route. Although they reached the learning criterion indicating perfect learning, the number of errors in the test trial was higher in the spina bifida group than in the control group. These results support the assumption that the spatial knowledge of children with spina bifida is impaired not only in small-scale spaces, as has been shown previously (e.g. Sand et al., 1973), but also in large-scale environments. Second, controlling again for the performance IQ, children with spina bifida did not show substantial deficits in their landmark knowledge: Even they recalled less landmark identities as well as fewer landmarks at their correct location, these differences were not significant.

Taken together the results demonstrate that children with spina bifida indeed show severely limited *route* knowledge compared to matched control children, but relatively unimpaired *landmark* knowledge. Since we matched the two groups with respect to the verbal IQ and controlled for the performance IQ, the limited route knowledge is not attributable to differences in cognitive abilities and might instead be attributable to the restricted mobility of the children with spina bifida. In this context it is quite interesting that only the more behaviour based measurement of route knowledge, the number of learning trials, correlated substantially with the age children with spina bifida learned to walk. Therefore, we might conclude that measurements which are more behaviour based rely more on the mobility of the patients compared to measurements which are more memory based, like the landmark knowledge recall test. This is a very important point, because it reveals that patients who are impaired in their mobility do not suffer from impaired spatial knowledge in general. Therefore, it is necessary to carefully distinguish between different kinds of spatial knowledge.

Investigating the route knowledge in more detail, the data suggest that it is more crucial for children with spina bifida than for healthy children to have an environment rich of landmarks during the learning of a route in a large-scale environment. When landmark information was absent which was the case in the test trial, children with spina bifida had difficulties to find their way. The children with spina bifida made many errors in the test trial in which the landmarks were absent whereas the number of errors of the healthy children was quite small. While children with spina bifida seemed to navigate through an environment on the basis of previously learned landmark information, their healthy peers seemed to rely more on the spatial configuration of the environment. These results are in accordance with other studies showing that younger children (8 years), which are cognitively less developed, rely more on landmarks when learning a route than older children (Beilstein & Wilson, 2000; Blades & Medlicott, 1992; Blades & Spencer, 1990). Studies which emphasize the importance of landmarks on special spatial knowledge tasks for adults and middle school-aged children (Cornell et al., 1989; Cornell, Heth, & Rowat, 1992) also strengthen our position in that cognitively less developed participants used proximal landmark information to learn a route.

Beside the differences in our spatial knowledge task which investigated route knowledge explicitly, we found no significant group differences in tasks that more explicitly relied on memory recall. This result is in accordance with other studies investigating spatial memory in small-scale tasks which also found no differences in sequential position learning tasks between spina bifida and healthy children (Dennis et al., 2002; Mammarella et al., 2003).

Overall, our study replicated the findings of Cohen and Schuepfer (1980) and Jansen-Osmann and Wiedenbauer (2004b) concerning the relevance of landmarks while learning a route in a virtual environment with impaired and healthy children. The possible argument that performance differences between the spina bifida group and the healthy control group might be attributed to different levels of familiarity with computer games has to be rejected. Prior to the testing, we asked the children if they had played computer games before. All children—the able-bodied as well as the spina bifida children—were used to playing computer games. Furthermore, in none of our previous studies we found an effect of frequency of computer use on spatial behaviour and spatial knowledge in children (Jansen-Osmann & Wiedenbauer, 2004a, 2004b, 2004c). To summarize, the results of our study show that virtual environments are an appropriate method for investigating spatial knowledge of physically disabled children. Regarding training or transfer effects to real environments, the advantages and disadvantages of using virtual environments for children with disabilities are discussed in detail elsewhere (McComas, Pivik, & Laflamme, 1998). We found evidence that the acquisition of route knowledge in a large-scale environment is impaired in children with spina bifida. The next step would be to investigate the origin of these impairments in more detail.

Since we controlled for the cognitive differences between children of spina bifida and healthy children, the limited performance of the children with spina bifida might be

traced back to their mobility deficit. This is in line with a study of Stanton et al. (2002), who showed that early mobility and self-governed exploration of the environment seem to be important in the development of spatial knowledge. Furthermore, the detrimental effects of restricted early spatial experiences might continue to affect spatial knowledge in the patients' teenage years (Simms, 1987). Additionally, the results are also in line with the recently published studies showing that learning of movements changes the cortical plasticity (e.g. Draganski et al., 2004) which indicates that mobility might have an long lasting effect.

To clarify the relation between mobility impairment and spatial behaviour, further studies are needed. Studies with other patient groups whose mobility is impaired but who do not differ in their general intelligence should be conducted. The age in which they learned to walk and the age in which the mobility impairment emerged, respectively, has to be controlled. Furthermore, the consequences of the mobility impairment on spatial abilities have to be investigated in more detail: Are children with spina bifida more retarded due to a lack of locomotion experience or because they had fewer opportunities to choose their ways actively on their own. Virtual environments provide an appropriate method to investigate these issues in detail.

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