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Original Communication

Wayfinding Behavior and Spatial Knowledge of Adults and Children in a Virtual Environment: The Role of the Environmental Structure

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This study investigated the effect of regularity in environmental structure on wayfinding behavior and spatial knowledge. A total of 60 participants (7- to 8-year-olds, 11- to12-year-olds, and adults) performed self-determined movements in a desktop virtual environment. In almost all measurements of wayfinding performance and spatial knowledge an overall developmental progress from younger children to adults was found. In contrast, exploration behavior did not differ between adults and children Furthermore, the environmental structure tended to influence only the wayfinding performance of younger children, but did not have any effect on the exploration behavior and the spatial knowledge of children or adults. This outcome supports the idea of a dissociation between exploration behavior, wayfinding performance and spatial knowledge as distinct aspects of spatial cognition.

Keywords: spatial cognition, wayfinding performance and behavior, spatial knowledge, children, development, virtual environments

Wayfinding behavior and spatial knowledge constitute the two main topics of spatial cognition research with respect to a large-scale or environmental space, that is, a space which is not perceivable from one single vantage point (e.g., Canter & Craig, 1981). Unfortunately, these two aspects of spatial cognition (i.e., wayfinding behavior and spatial knowledge) have been addressed separately most of the time, although they are obviously interrelated. It is the main goal of this study to investigate the influence of one particular but mostly neglected factor, namely the environmental structure, on both wayfinding behavior and spatial knowledge for adults as well as for children.

Wayfinding behavior is made up of the performance to find a way (the wayfinding performance) as well as the orientation behavior in a new environment (exploration behavior) (e.g., Blades, 1997; Jansen-Osmann & Fuchs, 2006). Spatial knowledge, on the other hand, is defined as landmark knowledge, route or procedural knowledge, and survey knowledge (Golledge, 1987; Siegel & White, 1975; Thorndyke, 1981), the latter referring to the hierarchical organization of spatial knowledge (Hirtle & Jonides, 1985; Stevens & Coupe, 1978; for comprehensive studies see e.g., McNamara, 1986; McNamara & LeSueur, 1989; McNamara, Hardy, & Hirtle, 1989; McNamara, Ratcliff, & McKoon, 1984). Some assumptions, although underspecified, exist about the relationship between wayfinding behavior and spatial knowledge acquisition: Liben (1988, 1999) distinguished between doing and knowing in spatial cognition research. Similarly, Creem and Proffitt (1998, 2001) assumed that there are two different systems for processing spatial information: on the one hand, a perception-action system where spatial information is provided for guided action or motor responses, and on the other hand a cognitive system which contains internal representations. Whereas wayfinding behavior is based on viewpoint updating, the measurements of spatial cognition tasks demand a cognitive processing of spatial information. Additionally, our own studies provided evidence that different factors influence these two aspects in a differential way: Whereas the structuring of space by color (Jansen-Osmann & Wieden-

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bauer, 2004a) as well as the existence of landmarks (Jansen-Osmann & Fuchs, 2006) influenced the wayfinding behavior, neither of the two factors did have any effect on spatial knowledge. On the other hand, learning a schematic map influenced spatial knowledge but did not have any effect on the wayfinding behavior (Jansen-Osmann, Wiedenbauer, Schmid, & Heil, 2007). These data suggest that despite the fact that wayfinding behavior and spatial knowledge are obviously interrelated, they represent distinct aspects of spatial cognition, as it is possible to double dissociate them experimentally.

Quite an interesting question is how wayfinding behavior and spatial knowledge develop during childhood. According to Piaget (1948), spatial cognition is assumed to develop from a topological to a Euclidian comprehension at the age of 9 to 10 years, an assumption which is taken into account by Siegel and White (1975). These authors propose a developmental progress from landmark to route and to survey knowledge, which was at least partly confirmed by an empirical study by Cousins, Siegel, and Maxwell (1983). It was evident in route learning tasks that young children at the age of 7 to 8 years rely more on the existence of landmarks than 11- to 12-year-old children and adults do (e.g., Cohen & Schuepfer, 1980) and that they depend more on the advice to notice landmarks (e.g., Cornell, Heth, & Broda, 1989). Environmental factors such as landmarks are therefore essential for learning a route. All these tasks, so far, have in common that they investigate the performance of learning a determined route but do not investigate the behavior when exploring an unknown environment. Furthermore, they do not show how wayfinding behavior and spatial knowledge develop out of that exploration behavior.

As a consequence, it seems important to reveal in much more detail how different environmental factors influence wayfinding behavior and spatial knowledge. One factor, though mostly neglected, is the regularity or symmetry of the environmental structure, which can be described completely in terms of the relative position of points, lines and angles within a space (Learmonth, Newcombe, & Huttenlocher, 2001). Unfortunately, only a single theoretical assumption regarding the influence of the environmental structure in a large-scale space exists: *The regularity hypothesis* by Thorndyke and Hayes-Roth (1982) assumes that the regularity of an environment has an effect on how rapidly a person is able to learn spatial relationships. If an environment is quite regular, locations may be determined by a coordinated frame of reference, whereby the entire environment is coded in relation to abstract axes defining the grid (Hart & Moore, 1973; Piaget & Inhelder, 1967). In an irregular environment, however, a coordinated frame of reference is difficult to use. Although the regularity hypothesis describes the structural influence in a large-scale space on a theoretical level, the empirical basis regarding the influence of the environmental overall structure in a large-scale space is scarce. Only very few studies investigated its impact on spatial knowledge acquisition (Ruddle & Péruch, 2004; Werner & Schmidt, 1999); its impact on wayfinding behavior, however, still needs to be determined. The main results of these few studies with adults suggest that people interpret the spatial structure of an environment in terms of a spatial reference system and that structure plays an important role in spatial memory.

The influence of the environmental structure from a developmental point of view was investigated only in a single study with children (Herman, Blomquist, & Klein, 1987), and even this study was restricted to spatial knowledge acquisition but completely disregarded wayfinding behavior. Herman et al. (1987) examined spatial knowledge acquisition of 8-and 11-year-old children and adults in environments with either a rectangular or a curved structure. Both environments were quite regular, as they were both symmetrical and differed only with respect to the kind of angles (orthogonal versus curved). Participants were driven through the environments in an automobile three times and made direction and distance estimations to target locations after each trip. The 8-year-olds had more difficulties than the older children and adults, but performance improved as participants became increasingly familiar with the environment. Most importantly, however, the structure of the environment did not have any effect on participants' performance. This lacking influence of the environmental structure, however, may have had different reasons: First of all, although the environments differed with respect to the kind of angles, both were regular. Secondly, only few aspects of spatial knowledge (direction and distance estimations) were taken into account, whereas others like configurational measurements (drawing of a map) were completely disregarded. Thirdly, wayfinding behavior was not investigated at all. And finally, children were not allowed to explore the environment on their own, which is critical in view of the well-known results that self-determined exploration facilitates spatial knowledge acquisition of younger children (Feldmann & Acredolo, 1979; Herman, Kolker, & Shaw, 1982). One has to conclude that there are still many open questions regarding the influence of the environmental structure on wayfinding behavior and spatial knowledge, in general, and even more so from a developmental perspective.

The main goal of the present study, therefore, was to investigate in more detail, also including a developmental approach whether the regularity and symmetry of a large-scale environment influences wayfinding behavior and spatial knowledge. We decided to manipulate both regularity and symmetry at the same time in order to increase the degree of manipulation, in contrast to the environments in the study of Herman et al. (1987) that were quite regular and differed only with respect to the kind of angles. In our study, regularity was varied not only by modifying the kind of angles (only 45° and 90° angles in the regular world) but also by manipulating the symmetry of the environment. This manipulation was chosen to obtain two different environments which still are comparable regarding the length of the routes, the number of angles, etc. In contrast to Herman and colleagues (1987), we chose a virtual environment situation which can be explored in a self-determined way (for a comprehensive discussion of the advantages and drawbacks of desktop virtual environments in spatial cognition research with children, see Jansen-Osmann & Fuchs, 2006; Jansen-Osmann & Wiedenbauer, 2004a; 2004b; 2004c). Although the disadvantage of this method is that the exposure to the environment cannot be strictly controlled, it seems to be closer to reality. Moreover, it has been shown that allowing people to navigate on their own leads to a better performance than passive exposure to a desktop virtual situation (Farrell, Arnold, Pettifer, Adams, Graham, & MacManamon, 2003). Furthermore, we investigated not only spatial knowledge acquisition but also wayfinding behavior, exploration behavior (i.e., peoples' behavior when exploring an environment for the first time), and wayfinding performance (i.e., their performance of effectively navigating in that environment).

Our study aimed at giving insights into spatial cognition development by investigating two points which have not yet been examined in detail: First of all, we investigated the development of exploration behavior, wayfinding performance, and spatial knowledge acquisition in one single study. Secondly, we measured the influence of the environmental structure on these three different aspects of spatial cognition.

At this point, we do not know anything about possible differences of the exploration behavior in an irregular and asymmetric versus a regular and symmetric environment in children at school age and in adults yet. Concerning wayfinding performance, one might assume that younger children might experience more difficulties to find their way in an irregular environment which is also not symmetrical. This assumption is based on the fact that a symmetrical layout and right angles are consistent with the bilateral symmetry of our body and that younger children are more likely to direct their wayfinding performance in line with egocentric frames of reference, which might result in a greater importance of and their reliance on their body axes. Regarding spatial knowledge acquisition, we assume a developmental progress from childhood to adulthood (e.g., Siegel & White, 1975). In sum, we investigated the influence of the environmental structure in much more detail than Herman et al. (1987) did before.

Method

Participants

Forty children from two age groups (mean age: 7.85 years and 11.20 years) and twenty adults (mean age: 24.15 years) participated in the study. There were 10 females and 10 males in each age group. Children were recruited through advertisements in local newspapers stating that we were looking for children to participate in an experiment of spatial cognition in a virtual environment. Their participation was remunerated with € 10.–. Prior to testing, all parents gave their informed written consent for their children to participate in the study. The local ethics committee approved the experimental procedure.

Materials

The study was conducted in a virtual world using the software 3D GameStudio A5. By varying both the symmetry and the regularity of the maze at the same time, two versions of the maze were realized: one with a regular, symmetrical structure and one with an irregular, asymmetrical structure. The *regular virtual maze* (Figure 1a) consisted of three main route-networks, quadratically arranged and linked by eight routes which branched off at an angle of either 45° or 90°. As a consequence, at decision points routes branched off at an angle of either 0° (straight ahead), 45°, 90°, or 135°. In the *irregular maze* (Figure 1b), the routes were beveled, and the right upper edge was missing. The plan of the irregular maze lacked a complete quadratic shape.

The virtual world was projected onto a 17-inch flatscreen monitor. The distance between monitor and participant was 0.5 m. Participants explored the simulated maze by using a joystick. The starting position was set in a small dead end with brown walls. All other walls in the maze were grey. Therefore, the starting position was identifiable during each walk through the virtual world. During the learning and the test phase, a toy figure resembling a popular figure, Bob the Builder, was placed in the second route-net-

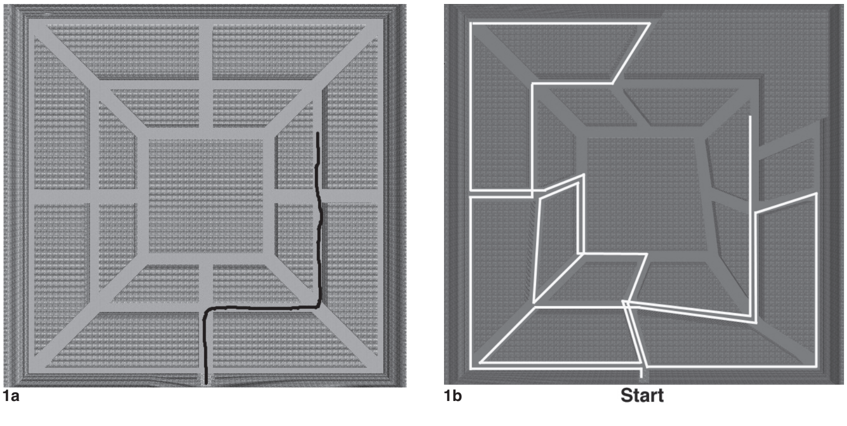

Figure 1. Figure 1a shows an overview of the regular maze. The shortest route to reach the target figure is marked. Figure 1b shows an overview of the irregular maze. The white line marks the route walked by an adult in the exploration phase.

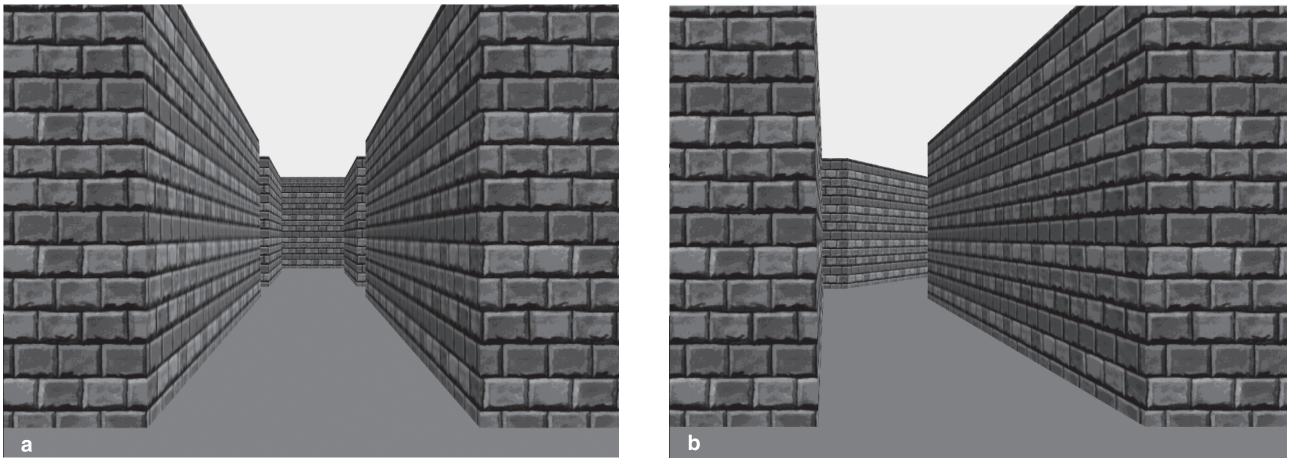

Figure 2. Snap shot of the regular (Figure 2a) and of the irregular maze (Figure 2b).

work in the right half of the maze and served as the target figure. Figure 2 shows a snapshot of the regular maze (Figure 2a) and of the irregular maze (Figure 2b).

Procedure

Individual test sessions took place in a laboratory at the Heinrich-Heine-University of Düsseldorf and lasted for about 30 min. At first, the children's and adults' computer experience was registered: They were asked how often they play computer games (in hours per week), which games they play (if the games contained wayfinding or maze elements or more strategic aspects), and which input device they used for playing. All participants were then given the opportunity to practice handling the joystick by navigating through another (non experimental) maze. Their walking speed in this learning maze as well as in the following experimental maze approximated real-life walking speed. The joystick had to be pushed until dead stop so that velocity remained constant. Rotation and translation velocities were the same. Participants from each age group were randomly assigned to one of the virtual mazes (regular vs. irregular). There were three experimental phases (exploration, learning, and test phase). In the exploration phase, participants were familiarized with the maze. The learning phase was assumed to shed light on the wayfinding performance, whereas the measurements of the test phase assessed participants' spatial knowledge. During all experimental phases, each participant's position was recorded six times per second while they moved through the virtual maze, and their paths taken in each trial were plotted onto an overview (e.g., see Figure 1b, in which the route walked by one participant in the exploration phase is marked). This procedure allowed registering the distance walked in units of the software and retracing the route walked.

Exploration Phase

Participants received the following instruction: "Now, you have to explore an unknown virtual environment without any objects. Please push the joystick until dead stop and try to explore the whole maze. This phase will end after 3 min." Since participants navigated in a self-determined way, the exact path used during the exploration phase varied between participants. The behavior in the exploration phase was measured by the distance walked and the number of turns chosen.

Learning Phase: Wayfinding Performance

After having explored the maze for 3 min, participants received the following instruction: "You have to explore the maze again, but now it is your task to find a target toy-figure, namely *Bob the Builder*." If they did not know Bob the Builder, the figure was described. After having found the target figure, participants had to find the shortest way from the starting position to the target figure in two consecutive trials (learning criterion). This shortest route (Figure 1a) was defined as the one with the shortest distance to be walked and containing not more than two turns. Only one correct route was possible: Participants had to turn right at the second intersection and turn left at the next intersection. All other possible routes were longer or had more turns. In contrast to the exploration phase in which the task was merely to explore the maze, the wayfinding behavior in the learning phase was constrained, that is, the target figure had to be reached by choosing two turns only. We chose this particular route because previous studies had shown that this was an understandable learning criterion even for younger children (Jansen-Osmann & Wiedenbauer, 2004b; Jansen-Osmann et al., 2007).

The wayfinding performance was measured by the distance walked and by the number of the turns chosen, however, only in the second learning trial. We chose the second trial for analysis because participants knew at this point where Bob the Builder could be found. In addition, the number of trials needed to reach the learning criterion in the learning phase was counted. Each walk from the starting position until the target figure was reached, was defined as one trial.

Test Phase: Spatial Knowledge

After reaching the learning criterion, the participants completed the following tasks:

Direction estimation task

At first, direction estimation was assessed. The participant's viewpoint was set in front of the target figure. Participants were instructed to estimate the direction from the target figure to the starting position by first rotating the joystick in the direction of the starting position and then pressing a special joystick button. Corrective rotations were allowed before pressing the button. The dependent variable was the angular difference between the estimated and the correct angle.

Detour task

Each participant had to complete two detour tasks. In both tasks, the originally shortest way was blocked by a barrier. Participants had to find a detour, that is, an alternative short way, first from the target figure to the starting position (Detour 1) and then vice versa (Detour 2). Again, the participant's viewpoint was set in front of the target figure. To analyze the performance in the two detour tasks, the distance walked was registered in units of the software (SU). The experimental factor direction (from target to start: Detour 1; and from start to target: Detour 2) was introduced for the analysis of the detour task.

Map task

All participants were asked to draw an overview of the maze. Thereafter, they were given a ready-made overview of the maze and were asked to mark the position of the target figure. This task was not limited in time. To analyze the precision of the acquired spatial knowledge, a) the accuracy of the drawn map *(map correctness score)* and b) the *linear distance* (in mm) from the marked to the correct position of the target figure in the overview were computed. Participants' drawings of the maze were coded by two independent raters. The map correctness score indicated how many of the following characteristics were observable in a drawing: a) a rectangular structure, b) an angular configuration, c) symmetry of the maze, d) skew turnoffs, e) drawing traceable, f) ring structure, g) the correct sector from start to target, and h) similar lengths of single route segments. Furthermore, one point was assigned if i) the number of intersections drawn differed no more than 25% from the correct number. All these variables represent the essential features of the maze. For each of the observable characteristics one point was assigned. The maximum score that could be obtained was nine. Cronbach's Alpha, indicating the consistency of the nine measurements of the coding scheme, was sufficiently high (.74).

Results

Gender Differences

Gender differences were not the main focus of the study. However, as gender differences are often stated in spatial cognition research (Lawton, 1994), they will be reported in short for the sake of completeness. Gender differences were found only regarding exploration behavior and the map tasks (map correctness score and linear distances). In the exploration phase, females ($\bar{\chi} = 6712.50$, $SE = 207.24$) walked shorter distances than males ($\bar{\chi} = 7375.87$, $SE = 146.38$), $F(1,48) = 7.03$, $p < .05$, $\eta^2 = .13$. The map correctness score of females ($\bar{\chi} = 6.37$, $SE = 0.55$) was lower than the males' score ($\bar{\chi} = 8.37$, $SE = 0.39$), $F(1,48) = 9.29$, $p < .01$, $\eta^2 = .13$, and the registered straight line distance was significantly shorter for males ($\bar{\chi} = 29.27$, $SE = 3.9$) than for females ($\bar{\chi} = 44.47$, $SE = 4.95$), $F(1,42) = 6.98$, $p < .05$, $\eta^2 = .09$. This pattern of results held true for all three age groups.

Computer Experience

A univariate analysis of variance revealed a significant difference in computer-experience (hours per week) between age groups, $F(2,57) = 5.35$, $p < .01$, $\eta^2 = .16$. Older children ($\bar{\chi} = 2.3$, $SE = .7$) played computer games more often than younger children ($\bar{\chi} = 0.58$, $SE = 0.23$) and adults ($\bar{\chi} = 0.45$, $SE = 0.22$) (sequentially Bonferroni adjusted, see Sokal & Rohlf, 1995). However, no significant correlations between computer experience and the measurements of wayfinding performance and spatial knowledge, described in detail in the following sections, were observed. Moreover, no gender effects were observed, $F(1,54) = 2.52$.

Exploration Phase: Exploration Behavior

A univariate analysis of variance did neither reveal any significant main effects nor any interaction for the distance walked (age group, $F(2,54) = .36$; type of maze, $F(1,54) = 1.29$; and interaction between age group and type of maze, $F(2,54) = .69$) nor for the number of turns chosen (age group, $F(2,54) = 1.58$; type of maze, $F(1,54) = 0.25$; and interaction between age group and type of maze, $F(2,54) = 0.47$), in the exploration phase.

Learning Phase: Wayfinding Performance

Distance Walked and Number of Turns Chosen

A univariate analysis of variance did neither reveal any significant main effect of age group, $F(2,54) = .69$ and type of maze, $F(1,54) = 0.03$, nor any interaction between these two factors, $F(1,54) = 1.85$, for the distance walked in the second trial. Concerning the number of turns chosen, a univariate analysis of variance revealed no significant main effect of age group, $F(2,54) = .69$ and type of maze, $F(1,54) = 0.03$ but a marginally significant interaction between both factors, $F(2,54) = 3.11$, $p = .053$, $\eta^2 = .1$ (Figure 3). This effect is based upon the different number of turns chosen as a function of type of maze by the adults, $F(1,18) = 3.31$, $p = .085$, $\eta^2 = .16$, and the younger children, $F(1,18) = 3.89$, $p = .064$, $\eta^2 = .19$, however, both effects are only marginally significant. Adults made more turns in the regular maze ($\bar{\chi} = 9.6$, $SE = 3.28$) than in the irregular one ($\bar{\chi} = 3.4$, $SE = 0.89$), whereas younger children made fewer turns in the regular maze ($\bar{\chi} = 5.3$, $SE = 1.68$) than in the irregular one ($\bar{\chi} = 12$, $SE = 2.94$). No difference was made by the older children, $F(1,18) = 0.14$, irregular: = 10.2, $SE = 3.57$, regular: = $\bar{\chi}$ 8.6, $SE = 2.19$. The distance walked and the number of turns chosen in the second learning trial correlated substantially, $r = .96$, $p <.001$.

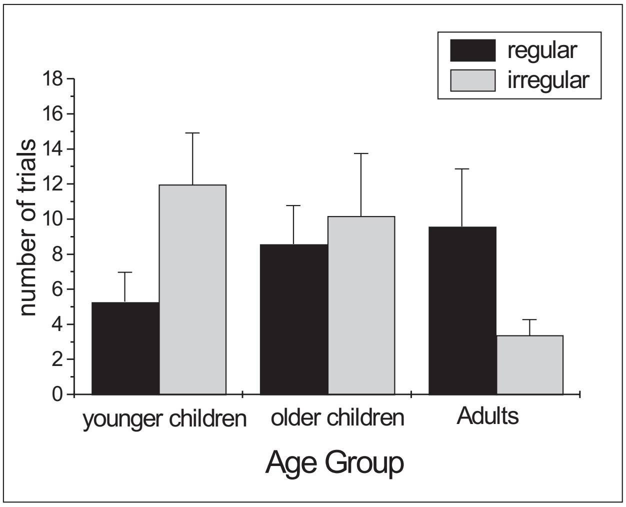

Figure 3. Mean number of turns in the second learning trial participants used to find the target figure as a function of age group and type of maze (error bars indicate standard errors).

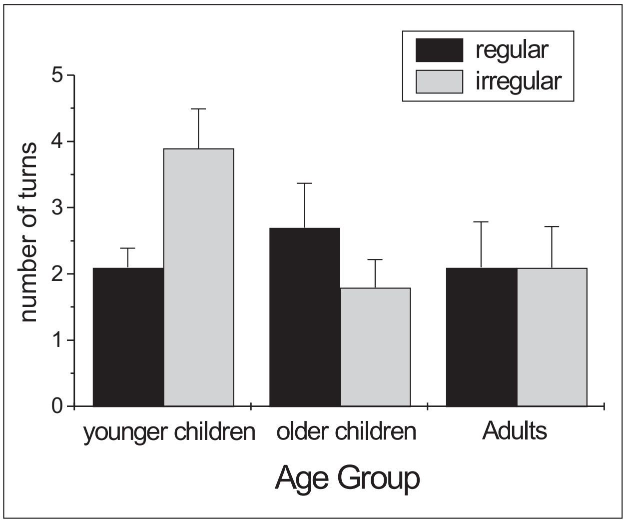

Figure 4. Mean number of trials participants needed to reach the learning criterion as a function of age group and type of maze (error bars indicate standard errors).

Number of Learning Trials

A univariate analysis of variance revealed a marginally reliable interaction of the factors age group and type of maze, $F(2,54) = 2.98$, $p = .059$, $\eta^2 = .1$. No statistically significant main effects of age group, $F(2,54) = 1.34$, and type of maze, $F(1,54) = 0.33$, were found. Figure 4 shows the mean number of trials needed to reach the learning criterion. In the irregular maze, younger children ($\bar{\chi} = 3.9$, $SE = 0.61$) needed more learning trials than older children ($\bar{\chi} = 1.8$, $SE = 0.41$) and adults ($\bar{\chi} = 2.1$, $SE = 0.61$), whereas only the first comparison was significant, $F(2,27) = 4.18$, $p <.05$, $\eta^2 = .24$. No such effect was observed for the regular maze, $F(2,27) = 0.74$. The difference in learning trials for younger children between the irregular ($\bar{\chi} = 3.9$, $SE = 0.61$) and the regular environment ($\bar{\chi} = 2.1$, $SE = 0.69$) was marginally significant, $F(1,18) = 3.75$, $p = .069$, $\eta^2 = .17$. No such effect was observed for older children or adults (Figure 4).

Test Phase: Spatial Knowledge

Direction Estimation Task

A univariate analysis of variance revealed only a significant influence of the factor age group, $F(2,54) = 3.65$, $p <.05$, $\eta^2 = .12$). There was neither a significant effect of the type of maze, $F(1,54) = 0.07$, nor an interaction between the factors age group and type of maze, $F(2,54) = 0.45$. The direction estimation was less accurate with younger children ($\bar{\chi} = 98.05°$, $SE = 21.8$) than with older children ($\bar{\chi} = 61.65°$, $SE = 21.15$) and adults ($\bar{\chi} = 25.0°$, $SE = 10.25$). Only the difference between younger children and adults reached statistical significance (Bonferroni adjusted).

Detour Task

When participants had to find the alternatively shortest way from the start to the target and vice versa (the originally shortest route was blocked by a barrier), an analysis of variance revealed only a significant main effect of the factor age group, *F*(2,54) = 7.76, *p* = .001, η^2 = .22. Younger children ($\bar{\chi}$ = 5970.88 SU, *SE* = 622.22) walked significantly longer distances than older children ($\bar{\chi}$ = 3742.2 SU, *SE* = 281.54) and adults ($\bar{\chi}$ = 3789.00 SU, *SE* = 385.53), the latter two groups did not differ (Bonferroni adjusted). There was no difference between the overall distance walked in Detour Task 1 and 2 (factor direction), *F*(1,54) = 0.76, neither any effects of type of maze, *F*(1,54) = 0.66, nor any significant interactions.

Map Task

Map correctness score

A univariate analysis of the map correctness score revealed a significant main effect of the factor age group, *F*(2,54) = 3.32, *p* <.05, η^2 = .12. Younger children ($\bar{\chi}$ = 6.05, *SE* = 0.62) obtained fewer points than older children ($\bar{\chi}$ = 7.9, *SE* = 0.60) and adults ($\bar{\chi}$ = 8.00, *SE* = 0.57). There was neither a significant influence of the factor type of maze, *F*(1,54) = 0.03, nor an interaction between both factors, *F*(2,54) = 0.47.

Linear distance

There was no significant influence at all (factor age group, *F*(2,54) = 1.12; factor type of maze *F*(1,54) = 0.37; interaction between both factors, *F*(2,54) = 1.60).

Correlation Between Wayfinding Performance and Spatial Knowledge

To investigate the relationship between wayfinding performance and spatial knowledge, the partial correlation between the measurements of wayfinding performance and spatial knowledge was calculated controlling for the factor age group. There was only one significant correlation, that is, between the number of trials to reach the learning criterion and the map correctness score (*r* = –.353, *p* <.01), but not between the number of trials to reach the learning criterion and direction estimation (*r* = .020), Detour Task 1 (*r* = .168, *ns*), Detour Task 2 (*r* = .088), and the linear distance (*r* = .105).

Discussion

The results are pretty straightforward and show different pictures regarding the developmental aspect and the regularity hypotheses: Concerning the developmental aspect, there was no difference in the exploration behavior between adults and children at school age. All age groups walked the same distance and chose the same number of turns. In contrast, a developmental progress from childhood to adulthood was observed in three of the four spatial knowledge measurements and in the wayfinding performance measurements that was even dependent upon the kind of environment regarding the number of trials to reach the learning criterion. This is one of the first studies evaluating how wayfinding behavior and spatial knowledge develop from the behavior in a new environment, in this case a virtual one. The results indicate that differences in behavior in an unknown environment might not be responsible for the differences observed between children and adults, but that the learning processes or, more generally, the cognitive abilities differ between children and adults. A study by Allen and Ondracek (1995) emphasizes the relationship between age-sensitive cognitive abilities and children's acquisition of spatial knowledge: For example, perceptual motor speed mediated the relationship between age and route knowledge. Another argument to support this conclusion is based on the observation that age differences are smaller in behavior-based measurements (exploration, wayfinding performance) compared to cognitive tasks (spatial knowledge tasks).

At present, it is difficult to know whether these age differences are due to the general cognitive development or rather to the specific spatial cognitive development. Recently, it was argued that there is no qualitative shift from topological to Euclidean coding but that, instead, much more changes in hierarchical coding take place (cf. Newcombe & Huttenlocher, 2000). As children become older they are more able to divide space into smaller categories, which helps them to act in the environment and to represent spatial information. One might speculate that in an environment without almost any landmark information, the environmental structure plays a main role and that hierarchical coding processes dominate, resulting in the age differences obtained in our study.

Concerning the empirical investigation of the regularity hypotheses, however, we were only partly successful because the regularity of the environment seemed to influence spatial cognition only in part (wayfinding performance) and only in younger children. The result that the wayfinding performance of older children and adults in this experiment was not influenced by environmental structure might be due to the fact that with increasing age, individuals might be more capable to regularize irregular features, as it was already shown in spatial memory research with adults (Montello, 1991; Tversky, 2000). Another explanation might be that wayfinding simply reflects an earlier stage of spatial learning and that spatial knowledge becomes gradually more and more independent of environmental structure. Moreover, as spatial knowledge and wayfinding are interrelated, this knowledge becomes gradually independent of regularity and irregularity. It is also probable that regularity did not influence exploration behavior because the learning in this phase did not have any goal.

Bearing in mind that this was the first study investigating the influence of environmental structure in large-scale space in a systematic manner, other studies will have to follow, with the aim to a) vary the regularity of the environment in different ways, b) diversify the space from small-to large-scale space, c) apply different wayfinding and spatial knowledge tasks, and d) test children of different age groups (from 3 to 14 years) and adults. For example, two regular environments might be used, differing only with respect to the angles like a rectangular and a circular environment. Additionally, more variations of symmetry should be investigated. Moreover, wayfinding behavior and exploration behavior should be examined in more detail. As we know that people use a variety of methods when solving orienting and wayfinding tasks in an environmental space (Cornell & Heth, 2000; Cornell, Sorenson, & Mio, 2003), it seems quite plausible to systematically vary the strategies used, for example, to give participants a hint to always walk back to the starting position in case of getting lost. Further evidence is necessary before we can conclude with certainty that the regularity of an environment only effects early spatial learning phases.

The complete lack of influence of the environmental structure on spatial knowledge is in accordance with the study of Herman et al. (1987). Given these results, together with the observation that environmental structure might indeed influence wayfinding performance, the data obtained strengthen the assumption of a dissociation between wayfinding performance and spatial knowledge. Such a dissociation is also supported by previous studies of our group (Jansen-Osmann & Wiedenbauer, 2004b; Jansen-Osmann et al., 2007). One might assume that in the wayfinding task, information is tied more strongly to the position of one's own body or viewpoint, rather than in the spatial knowledge tasks. Furthermore, it can be assumed that the position of one's own body or viewpoint might be defined more easily in a regular environment, because there, locations are learned in a coordinated frame of reference. Based on this point of view, it is not astonishing that environmental structure mainly influences those tasks which are mostly viewer-based. Our results suggest that the understanding of spatial development has to be changed from a mainly cognitive-constructive to a contextual perspective which assumes that spatial cognition is more than thinking about the environment (cf., e.g., Heft & Wohlwill, 1987).

Before specifically discussing age differences which might be due to the use of virtual environments, we will briefly discuss the observed gender differences. Females walked shorter distances in the exploration behavior phase than males, and they showed a worse performance on the map tasks. This result was independent of age. Taking into account that males often pay greater attention to configurational aspects like distance or direction and females use landmarks more frequently (cf. Dabbs, Chang, & Strong, 1998; Miller & Santoni, 1986), one might assume that men show a better performance in those tasks where configurational knowledge is explicitly retrieved. The assumption that some of the variance in spatial tasks results from the influence of prior computer experience (Waller, 2000; Waller, Knapp, & Hunt, 2001) might not hold true for the exploration behavior in this study. However, although females and males did not differ in their computer use, females might hesitate to push the joystick and explore the maze straight ahead. Because rotation and translation speed was controlled, we might assume that they stop more often than males.

Regarding age differences, we found for example, that the direction estimation in a virtual environment was less accurate with younger children than with adults, whereby it is important to note that the angular difference was very high (98.05°) with younger children, indicating that they had much difficulty in estimating a direction in the virtual world. The errors in direction estimation made by the adults correspond to those found in a study by Waller, Montello, Richardson, and Hegarty (2002), which indicates that direction estimations might be comparable in different desktop virtual environments. A new result in our study was that no differences between younger and older children and adults were found concerning the orientation dependency. In general, there was no evidence for an orientation-specific representation of the route: It was not easier for participants to find a detour when walking from the start to the target than vice versa. This is in line with the assumption that spatial memory is independent of orientation if self-determined exploration is allowed (Evans & Pezdek, 1980; Presson, DeLange, & Hazelrigg, 1989). In contrast, most studies in virtual environments show that spatial information learned in a virtual environment is orientation-specific (for an overview, cf. Christou & Bülthoff, 1999; Montello, Waller, Hegarty, & Richardson, 2004; Richardson, Montello, & Hegarty, 1999). Assuming that there is a developmental progress from childhood to adulthood, it is quite astonishing that we did not find any age-related differences regarding orientation specificity. Even though we know far more than we did a few decades ago about the capabilities of infants to coordinate information about static perceptual characteristics of objects (Newcombe & Sluzenski, 2004), it is surprising that no age differences in orientation dependency were found, given age-related changes in route coding. Further studies investigating the spatial and general cognitive abilities will have to be conducted to address this issue.

Finally, the robustness of our findings and the generalization using the desktop system need to be discussed. Further studies will have to be conducted which directly compare knowledge acquisition in real and virtual environments from a developmental perspective. There is evidence from studies with adults that at least the most important properties of the spatial representations that underlie spatial behavior can be analyzed in both real and virtual environments (Loomis, Blascovich, & Beall, 1999) and that testing in virtual and real environments leads to similar results (Péruch & Wilson, 2004). With the exception of two studies (Laurance, Learmonth, Nadel, & Jacobs, 2003; Plumert, Kearney, & Cremer, 2004), this comparison, however, is still missing in studies with children. Interestingly, Laurance and her colleagues showed that children use virtual space as if it was real space.

Conclusion

This study was a first step to investigate the influence of environmental structure on wayfinding behavior and spatial knowledge of children and adults in a virtual space. The main result is that the variation of the regularity of the environment indeed tended to influence the wayfinding performance of younger children but not their spatial knowledge. Age differences were found in almost all spatial tasks, except for exploration behavior. This might indicate that the cognitive development in general is important for spatial learning in a large-scale environment.

Even though the results reported here are quite promising, many questions still need to be addressed in more detail. Especially, the influence of different forms of regularity and geometric variation needs to be investigated, as it was done in studies of the geometric influence of a room's structure in younger children's re-orientation performance.

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