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Spatial knowledge of adults and children in a virtual environment: The role of environmental structure

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This study investigated the effect of environmental structure's regularity on spatial knowledge in a total of 60 participants: second graders, sixth graders, and adults. A desktop virtual environment was used in which participants moved in a controlled self-determined way. The regularity of environmental structure did not influence spatial knowledge as measured by direction estimations and distances walked in route knowledge and detour tasks. In all measurements, an overall developmental increase of achievement from second graders to adults was found. Furthermore, gender differences were found for children as well as for adults, favouring males in all measurements. In addition, orientation specificity of spatial representations was found for adults and for children. Thus, the results reveal a number of interesting aspects regarding spatial knowledge acquisition of children and adults by using a virtual environmental approach.

For a long time spatial cognition research investigated the factors that influenced the acquisition of spatial knowledge of a large-scale environment, i.e., a space, which is not perceivable from one single vantage point (see, e.g., Canter & Craig, 1981). It is the main goal of this study to investigate the influence of one particular but mostly neglected factor, namely the regularity of environmental structure, on spatial knowledge in adults as well as in

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children. Environmental structure can be described completely in terms of the relative position of points, lines, and angles within the space (Learmonth, Newcombe, & Huttenlocher, 2001). Spatial knowledge is defined as landmark knowledge, route or procedural knowledge, and survey knowledge (Golledge, 1987; Siegel & White, 1975; Thorndyke, 1981), which refers to the hierarchical organization of spatial knowledge (Hirtle & Jonides, 1985; Stevens & Coupe, 1978; for comprehensive studies see McNamara, 1986; McNamara, Hardy, & Hirtle, 1989; McNamara & LeSueur, 1989; McNamara, Ratcliff, & McKoon, 1984).

Two theoretical approaches regarding the influence of environmental structure

Until now, two theoretical approaches have existed, both of which are related to the influence of the environmental structure, i.e., the geometric module hypothesis and the regularity hypothesis. Studies with animals have shown that disorientated rats are guided by a kind of a "geometric module" (Gallistel, 1990). Rats failed to use salient landmark information when they had to reorient themselves in a rectangular box, but instead used the structure of the box itself for orientation (Cheng, 1986). Additionally, investigations carried out in a vista-space, i.e., a space that encloses the observer and where every object can be perceived from one viewpoint, revealed the importance of the geometrical properties of the environment on reorientation, especially for younger children between the age of 1.5 and 4 years (Gouteux & Spelke, 2001; Hermer & Spelke, 1994, 1996; Learmonth, Nadel, & Newcombe, 2002), whereby this result is discussed controversially (Hupbach & Nadel, 2005). Furthermore, Thorndyke and Hayes-Roth (1982) proposed the "regularity" hypotheses. They assume that the regularity of an environment affects how rapidly a person is able to learn the spatial relationships. If an environment is quite regular, locations might be determined by a co-ordinated 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 co-ordinated frame of reference is difficult to use. At present, the relationship between these two theoretical approaches is difficult to determine. Whereas the geometric module hypotheses is confirmed by investigations with animals and young children in a small-scale space, the regularity hypotheses describes the structural influence in a large-scale space, but empirical support is missing. To simplify matters, we will not try to distinguish between the geometric module and the regularity hypothesis but will instead consider them as similar efforts to specify the importance of environmental structure; first with empirical support with young children in a small-scale space, and second with theoretical assumptions about spatial cognition in a large-scale space.

The developmental perspective regarding the influence of environmental structure

In contrast to these theoretical approaches, the empirical basis regarding the influence of environmental structure in a large-scale space is scarce. Very few studies have investigated its impact on spatial knowledge acquisition with adults (Ruddle & Péruch, 2004; Werner & Schmidt, 1999). The absence of such studies is even more surprising from a developmental point of view, given that the claim of the importance of the regularity of the environment's structure for spatial cognition contrasts with Piaget's (1948) stage model of cognitive development. According to Piaget, spatial cognition develops from a topological to a Euclidian comprehension at the age of 9 or 10 years, an assumption that is taken into account by Siegel and White (1975). These authors propose a developmental progress from landmark knowledge to route and survey knowledge. If this holds true, then the large-scale environmental structure's regularity should not affect younger children's spatial knowledge, simply because, according to Siegel and White, these children should not yet be able to use this kind of configurational information. Even though they might be able to use some environmental feature like sharp angles as landmarks for the acquisition of route knowledge, they should not be able to use the overall configuration for the acquisition of survey knowledge. According to both the geometric module and the regularity hypothesis, however, even very young children should be able to use this kind of information. Whereas this ability was convincingly shown in small-scale space (i.e., Hermer & Spelke, 1994, 1996), the question of whether or not this holds true for large-scale space is still completely open with the exception of a single study by Herman, Blomquist, and Klein (1987). The authors examined spatial knowledge acquisition of adults and 8- and 11-year-old children in environments with either a rectangular or a curved structure. Both environments, however, were quite regular, because they were both symmetrical and only differed with respect to the kind of angles (orthogonal versus curved). Participants were driven in an automobile through the environments three times and made direction and distance estimations to target locations after each trip. Eight-year-olds had more difficulties than older children and adults, but performance improved as subjects became increasingly familiar with the environment. Most importantly, however, the structure of the environment did not have an effect on participants' performance.

This lack of an influence of the environment's structure, however, may have different reasons: First of all, although the environments differed with respect to the kind of angles, both were quite regular. Second, subjects were not allowed to explore the environment on their own, which is critical due to the well-known results that self-determined exploration facilitates spatial knowledge acquisition especially for younger children (Feldmann & Acredolo, 1979; Herman, Kolker, & Shaw, 1982). And finally, no gender differences were investigated, even though they are well known in spatial cognition research (for a review see Coluccia & Louse, 2004).

The goal of this study: a developmental and differential perspective

It is the main goal of this study to investigate whether the regularity of a large-scale environment affects spatial knowledge in more detail incorporating a developmental approach. First, we decided to manipulate both regularity and symmetry at the same time in order to increase the power of the manipulation, because the environments in the study of Herman et al. (1987) were quite regular and differed only with respect to the kind of angles. We varied the regularity not only by using different kinds of angles (only 45° and 90° in the regular world), but also by manipulating the symmetry of the environment. This manipulation was chosen to obtain two different environments, which were still comparable regarding the length of the routes, the number of angles, etc. Second, 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, 2006; Jansen-Osmann & Wiedenbauer, 2004a; 2004b; 2004c). In our former studies we had used a completely self-determined exploration phase, which facilitates the spatial knowledge acquisition of young children (Feldmann & Acredolo, 1979; Herman et al., 1982) and leads to a better performance than passive exposure to a desktop virtual situation (Farell et al., 2003). But apart from these advantages, the actually explored parts of the maze might have differed substantially between participants and this could have influenced the spatial knowledge acquisition. Therefore, a *controlled* self-determined exploration phase was established in this study, making sure that all participants had explored all parts of the virtual environment. Third, we used a number of different measures of spatial knowledge in order to increase the sensitivity of our approach. Action-based measures like detour tasks and direction estimations were used instead of more abstract variables like map drawing. The latter might be more dependent upon general cognitive abilities favouring adults, whereas the former might be more appropriate for children because no cognitive transformation is required (see, e.g., Jansen-Osmann, 2006). Finally, our focus was on gender differences. In general, gender differences in spatial cognition research are well known, especially for some kinds of spatial ability like mental rotation, where males outperform females on quite a regular basis (e.g., Harshman, Hampson, & Berenbaum, 1983; Sanders, Soares, & D'Aquila, 1982). With respect to the strategies used for spatial orientation, several studies have shown that males paid more attention to configurational aspects like distances or directions, whereas females more frequently used landmarks themselves (e.g., Dabbs, Chang, & Strong, 1998; Miller & Santoni, 1986). This result was confirmed by studies that used self-report questionnaires for strategies (Lawton, 1994, 1996): females rely more on landmarks and on procedural "route" strategies than males, who prefer configurational strategies. For children it was shown that gender differences emerge soon after 9 years of age: boys demonstrate better sense of orientation, whereas girls pay more attention to landmarks (Joshi, MacLean, & Carter, 1999). Based on these findings, we hypothesized that males should use configurational information more effectively than females.

Overall we investigated whether a difference exists concerning the influence of environmental structure between children and adults. With this investigation we try to solve the contradiction between the geometric module/regularity hypotheses and Piaget's view of spatial cognitive development with children of school age: if the assumption in line with Piaget's view is correct, the overall configuration should not influence spatial cognition of the younger children at the age of 7–8 years. If the geometric module/regularity hypotheses holds true, even the spatial cognition of the younger children (and also that of the older children and adults) should be influenced by that configuration. Children of school age were chosen because a substantial improvement of spatial knowledge in a large-scale space was documented at this age (i.e., Cohen & Schuepfer, 1980; Jansen-Osmann & Wiedenbauer, 2004a).

METHOD

Participants

Forty children from two grade levels (second and sixth) and twenty adults participated. The mean age of the second graders was 7.45 years, that of the sixth graders was 11.4 years, and that of the adults was 24.85 years. There were 10 females and 10 males in each age group. Children were recruited through advertisements in local newspapers, which asked for people who were interested in participating in a virtual environment experiment, and received a payment of 10 €. Prior to testing, all parents gave their informed written consent for participation in the study. The local ethics committee approved the experimental procedure.

Materials

A questionnaire about the use of computer games and the joystick was constructed. Children and adults were asked how often they played computer games (in hours per week), what kind of games they played, and which input device they used for playing.

The study was conducted in a virtual world using the software 3D GameStudio A5. Varying both the symmetry and the regularity of the maze, two versions of the maze were realized: one with a regular and one with an irregular structure. The *regular virtual maze* (see Figure 1a) consisted of three main quadratically arranged route-networks linked by eight routes that branched off at an angle of either 90 or 45 degrees. As a consequence, at decision points routes branched off at an angle of either 0° (straight ahead), 90°, 45°, or 135°. In the *irregular maze* (see Figure 1b), the routes were sloping and the right upper edge of the maze was missing. Furthermore, the plan of the irregular maze did not have a complete quadratic shape.

The virtual world was projected onto a 17-inch flat-screen monitor. The distance between the monitor and the participant was 50 cm. Participants explored the simulated maze by using a joystick.

The start position was set in a small cul-de-sac with brown walls. All other walls in the maze were grey. Therefore, the start position was identifiable during each walk through the virtual world. Figure 2 shows snapshots into the regular maze (a) and into the irregular maze (b).

Three landmarks (a hammer, a plant, and a guitar) served as goal objects. Whereas the hammer was placed in the left half of the maze in the outer-route network (see location of number 1 in Figure 3), the plant was placed in the right half of the maze in the inner-route network (see location of number 2 in Figure 3). The guitar was located in the right half of the maze in the intermediate-route network (see location of number 3 in Figure 3).

Procedure

Individual test sessions lasted about 40 minutes and took place in a laboratory at the Heinrich-Heine-University of Düsseldorf. Each test session began with the registration of computer utilization behaviour, and all participants were given the opportunity to practice handling the joystick. Participants from each age group and sex were randomly assigned to one of the virtual mazes (regular vs irregular structure).

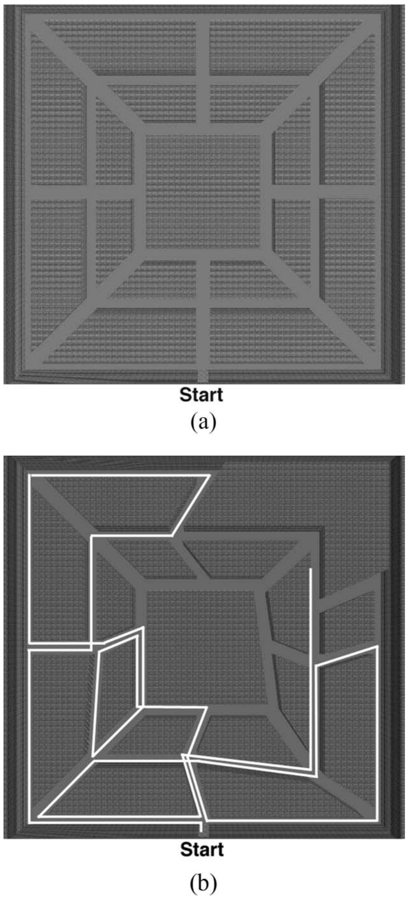
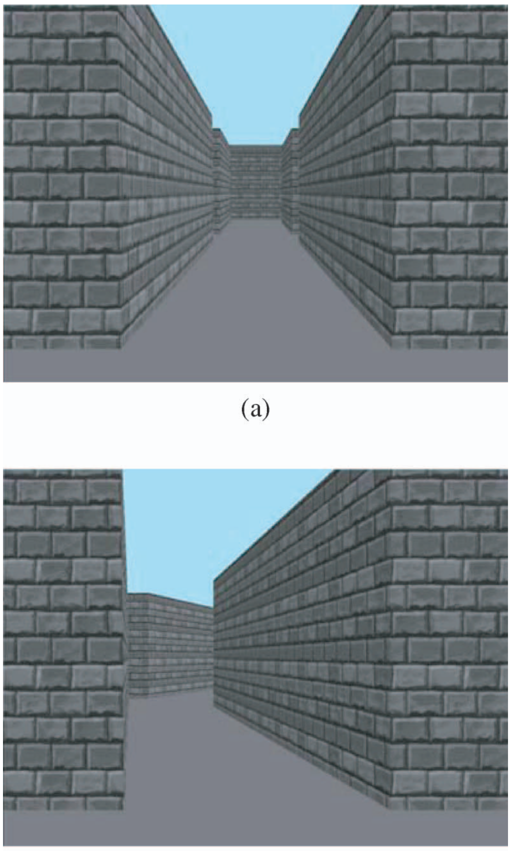


Figure 1. (a) An overview of the regular maze. (b) An overview of the irregular maze. The white line marks the route walked by an adult in the exploration phase.

There were two experimental phases, an exploration phase and a test phase. During both phases, each participant's position was recorded six times per second while they moved through the virtual maze. Their paths taken in each trial were plotted onto an overview. This allowed us to register the distance walked in units of the software and to retrace the route walked.

Exploration phase. Participants were told to explore an unknown virtual maze for five minutes as completely as possible. They were informed that they had to pass thirteen invisible points in the maze. They were further told that each of the invisible points was represented by a red can on



(a)

(b)

Figure 2. Snapshots (a) into the regular maze, and (b) into the irregular maze.

the upper margin of the display, and that each time they passed one of the invisible points a can would disappear. This was done to give subjects feedback of how much of the maze they already had explored. The exploration phase was finished when participants had passed all thirteen invisible points plus the three target objects. If participants had not completed the exploration of the entire maze within the five minutes, a virtual red can appeared at each of the not yet passed invisible points (see Figure 4). Participants were told that they should complete the exploration task. The still unpassed points were marked by a red can, which disappeared after passing. This was done to limit the differences with respect to the amount of experience with the maze. The time needed for

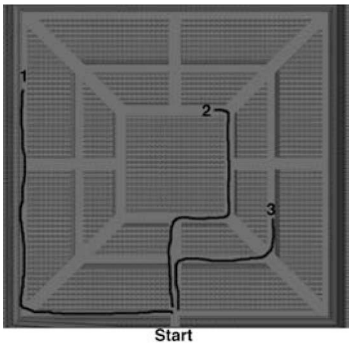


Figure 3. Overview of the regular maze. The shortest route from the start point to each of the three landmarks is marked.

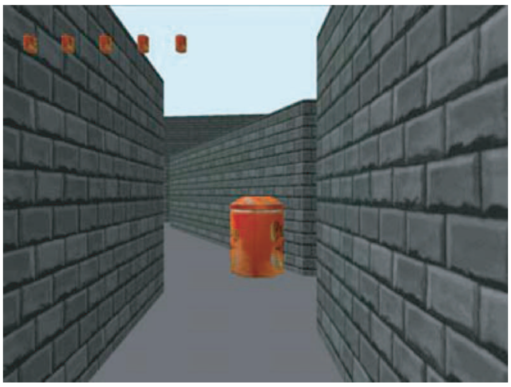


Figure 4. Snapshot into the regular maze during the exploration phase: The virtual cans at the top of the desktop represent the invisible points that the participant has not yet passed. The snapshot was taken after five minutes when all invisible points that the participant had not yet passed were marked by virtual cans in the maze.

the exploration was registered. Because participants were still navigating in a self-determined way, navigation behaviour in the exploration phase varied between participants (controlled free-exploration phase).

Test phase: Spatial knowledge. The subsequent test phase consisted of the following four spatial knowledge tasks. Dependent variables were either distance deviations, i.e., the difference between the distance actually walked and the distance of the optimal path, or direction estimation errors, i.e., the difference between the estimated and the correct direction.

Phase 1: Route knowledge task. Participants were instructed to walk from the start point to the three objects by the shortest possible route. Participants had two attempts for each object. They had to find the positions in the following sequence: hammer, plant, and guitar. The deviation between the (objectively) shortest paths (see Figure 3) and the distance actually walked was calculated (which would be zero for those participants who managed to walk the shortest way from the start point to the object). This difference score was averaged for the three objects as well as the two attempts for each object in order to increase the reliability of the score.

Phase 2: Direction estimation task I. The shortest way from the start point to the goal object was shown by a coloured highlighted path (see Figure 3 for an overview). The subjects had to follow this marked path. Having arrived at the respective object the marking disappeared and the direction to the remaining two other objects had to be estimated. For that, participants had to rotate the joystick in the direction of the other two objects consecutively and then had to press a special joystick button. Corrective rotations were allowed before pressing the button. The sequence of the estimation was as follows: from: "hammer" to "plant" and "guitar"; from "plant" to "hammer" and "guitar"; from "guitar" to "hammer" and "plant". The direction estimation was not done directly subsequent to the route knowledge task, but started with walking the highlighted path from the start to the goal objects to make sure that the initial position before the direction estimation was the same for all participants. The dependent variable was the absolute error between the estimated and correct angle averaged across all six direction estimations.

Phase 3: Direction estimation task II and detour tasks. This retrieval phase consisted of a direction estimation and a detour task for each object. First, the viewpoint of the participants was set in front of the start point facing into the maze. Participants were instructed to estimate the direction from the start point to the first object (in this case the hammer) by rotating the joystick in this direction. When the special joystick button was pressed in order to estimate the direction, a virtual barrier was visible the whole time, blocking the shortest route to the object. Participants were now instructed to find the alternatively shortest route from the start point to the goal object, in the first case, the hammer. Once they arrived at the goal object, participants were instructed to estimate the direction to the start point. Again, while pressing the joystick button, a virtual barrier blocking the shortest way back to the start point appeared, and the participants had to find the alternatively shortest route from the goal object to the start point. This procedure was repeated for all three objects.

The following four variables were analysed in this third test phase:

- Mean absolute error of the direction estimation from the start point to the three goal objects.
- Mean absolute error of the direction estimation from the three goal objects to the start point.
- Mean difference between the shortest path from the start point to the three goal objects and the distance actually walked.
- Mean difference between the shortest path from the three goal objects to the start point and the distance actually walked.

Phase 4: Survey knowledge task. To investigate whether participants had learned the configuration of the maze and the position of the objects in relation to each other, they had first to follow the shortest route from the start point to the hammer, again highlighted by colour cueing, and then they had to find the shortest route to the guitar in a self-determined way. This task was repeated twice in the following sequence (plant – hammer; guitar – plant). As it was possible that participants could reach the object from different directions, they were returned to the start point after each trial so that the point of departure was the same for all participants. The dependent variable was the mean difference between the distance walked and the shortest possible distance.

RESULTS

Computer experience

A univariate analysis of variance revealed a significant difference in computer experience (hours per week) between *age groups*, $F(2, 54) = 8.53$, $p = .001$, $\eta^2 = .06$. Older children ($\bar{x} = 5.28$, $SE = 1.38$) played computer games more often than younger children ($\bar{x} = 1.59$, $SE = 0.54$) and adults ($\bar{x} = 0.55$, $SE = 0.19$; Bonferroni adjusted). There was neither an influence of the factor *sex*, $F(1, 54) = 1.03$, *ns*, $\eta^2 = .03$, nor an interaction between *sex* and *age group*, $F(2, 54) = 0.14$, *ns*, $\eta^2 = .01$. Most importantly, there were no significant correlations between computer experience and any of the spatial-knowledge measurements.

Exploration phase

The distance walked in the exploration phase was analysed to make sure that differences in spatial knowledge were not attributable to differences in exploration behaviour. There was no significant difference of the distance walked between *age groups*, $F(2, 48) = 1.73$, *ns*, $\eta^2 = .07$, *sex*, $F(1, 48) = 2.47$, *ns*,

$\eta^2 = .05$ and *type of maze*, $F(1, 48) = 0.002$, *ns*, $\eta^2 = .00$. Moreover, neither a significant interaction between *age groups* and *sex*, $F(1, 48) = 2.47$, *ns*, $\eta^2 = .05$, *age groups* and *type of maze*, $F(2, 48) = .62$, *ns*, $\eta^2 = .03$, and *sex* and *type of maze*, $F(1, 48) = 1.81$, *ns*, $\eta^2 = .04$, nor the three-way interaction, $F(2, 48) = 0.98$, *ns*, $\eta^2 = .04$, turned out to be significant. Additionally, the time needed to complete the exploration phase was registered. There was a only a main effect of *age group* present, $F(2, 48) = 4.63$, $p < .05$, $\eta^2 = .17$. Younger children ($\bar{x} = 659.45$ s, $SE = 438.93$ s) needed more time to complete this phase than adults ($\bar{x} = 488.04$ s, $SE = 438.93$ s); the difference between older children ($\bar{x} = 613.55$ s, $SE = 438.93$ s) and adults did not reach significance. There was no significant effect of the time needed for the factors *sex*, $F(1, 48) = 2.28$, *ns*, $\eta^2 = .05$ and *type of maze*, $F(1, 48) = 1.53$, *ns*, $\eta^2 = .03$, and also no significant interaction between *age groups* and *sex*, $F(2, 48) = 0.259$, *ns*, $\eta^2 = .01$, *age groups* and *type of maze*, $F(2, 48) = 0.47$, *ns*, $\eta^2 = .02$, and *sex* and *type of maze*, $F(1, 48) = 1.01$, *ns*, $\eta^2 = .02$, and *age group*, *sex*, and *type of maze*, $F(2, 48) = 0.31$, *ns*, $\eta^2 = .013$. The fact, that younger children needed more time to complete the exploration phase but did not walk longer distances, gives a hint that their exploration behaviour is more variable in stopping and resting while exploring the maze. It does not differ from that of the adults, however, concerning the length of the explored route.

Test phase: Spatial knowledge

Phase 1: Route knowledge task. An analysis of variance with the factors *age group*, *sex* and *type of maze* revealed only significant main effects for the factors *age group*, $F(2, 48) = 14.41$, $p < .001$, $\eta^2 = .38$, and *sex*, $F(1, 48) = 26.03$, $p < .001$, $\eta^2 = .35$. As can be seen in Figure 5, when trying to walk from the start point to the goal objects by the shortest possible route, younger children ($\bar{x} = 3604.46$ SU, $SE = 438.94$) walked significantly longer distances than the older children ($\bar{x} = 2133.80$ SU, $SE = 335.87$), who in turn walked significantly longer distances than adults ($\bar{x} = 1395.44$ SU, $SE = 288.11$; Bonferroni adjusted). Furthermore, males ($\bar{x} = 1500.62$ SU, $SE = 180.83$) walked substantially smaller distances than females ($\bar{x} = 3255.15$ SU, $SE = 202.57$). The factor *type of maze*, $F(1, 48) = 3.17$, *ns*, $\eta^2 = .06$, did not influence the distance walked. There was neither a significant interaction between *age groups* and *sex*, $F(2, 48) = 0.60$, *ns*, $\eta^2 = .02$, *age groups* and *type of maze*, $F(2, 48) = 0.95$, *ns*, $\eta^2 = .04$, and *sex* and *type of maze*, $F(1, 48) = 0.74$, *ns*, $\eta^2 = .02$, nor a three-way interaction $F(2, 48) = 1.38$, *ns*, $\eta^2 = .06$.

Phase 2: Direction estimation task I. A univariate analysis of variance revealed only a significant influence of the factors *age group*, $F(2, 48) = 8.72$,

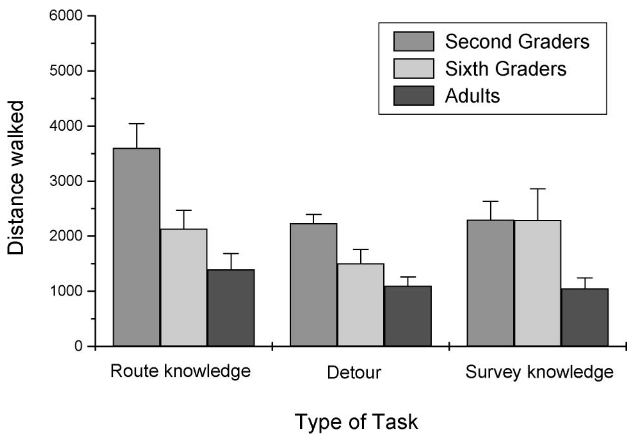


Figure 5. Means of the deviation of distance walked for all three walking tasks (error bars indicate standard errors).

$p = .001$, $\eta^2 = .27$ and *sex*, $F(1, 48) = 9.75$, $p < .01$, $\eta^2 = .17$. The direction estimation between objects was less accurate for the younger children ($\bar{x} = 65.39°$, $SE = 5.82$) than for the older children ($\bar{x} = 46.63°$, $SE = 4.69$) and the adults ($\bar{x} = 39.30°$, $SE = 3.88$) (see Figure 6). The difference between older children and adults did not reach statistical significance (Bonferroni adjusted). Males estimated directions more accurately ($\bar{x} = 42.19°$, $SE = 3.05$) than females ($\bar{x} = 58.09°$, $SE = 3.24$). The factor *type of maze*, $F(1, 54) = 1.05$, *ns*, $\eta^2 = .02$, did not influence the direction estimation. There was neither a significant interaction between *age groups* and *sex*, $F(2, 48) = 0.47$, *ns*, $\eta^2 = .02$, *age groups* and *type of maze*, $F(2, 48) = 0.43$, *ns*, $\eta^2 = .02$, and *sex* and *type of maze*, $F(1, 48) = 1.34$, *ns*, $\eta^2 = .03$, nor a three-way interaction $F(2, 48) = 1.45$, *ns*, $\eta^2 = .06$.

Phase 3: Direction estimation task II and detour tasks. An analysis of variance computed on the estimated direction from the start point to the objects and vice versa with the factor *direction*, *age group*, *sex*, and *type of maze* revealed significant main effects of the factors *age group*, $F(2, 48) = 7.75$, $p = .001$, $\eta^2 = .25$, *direction*, $F(1, 48) = 42.52$, $p < .00$, $\eta^2 = .47$, and *sex*, $F(1, 48) = 16.78$, $p < .01$, $\eta^2 = .26$. As can be seen in Figure 5, younger children ($\bar{x} = 44.79°$, $SE = 4.80$) had a higher estimation error than older children ($\bar{x} = 27.87°$, $SE = 4.84$) and adults ($\bar{x} = 25.20°$, $SE = 3.35$; Bonferroni adjusted). Furthermore, the error was higher in the condition of estimating the direction from the objects to the start point ($\bar{x} = 43.32°$, $SE = 4.35$) than vice versa ($\bar{x} = 21.91°$, $SE = 2.28$). This finding was qualified by a significant interaction between the factors *sex* and

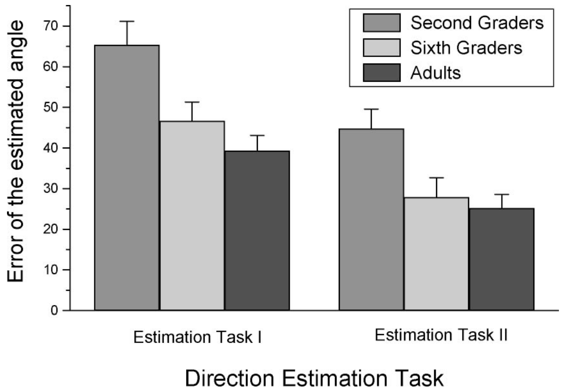


Figure 6. Mean direction estimation error for the first and the second direction estimation task (error bars indicate standard errors).

direction, $F(1, 48) = 7.23$, $p = .01$, $\eta^2 = .13$. The direction effect was reliably present only for the females ($\bar{x} = 56.77°$, $SE = 5.63$ vs. $\bar{x} = 26.51°$, $SE = 3.85$), but was reduced to a non-significant difference for the males ($\bar{x} = 29.87°$, $SE = 4.67$ vs. $\bar{x} = 17.32°$, $SE = 2.19$). The factor *type of maze*, $F(1, 54) = 1.67$, *ns*, $\eta^2 = .03$, did not influence the direction estimation. There were no other two-way significant interactions, nor any three- or four-way ones.

When participants had to find the alternative shortest way from the start to the objects and vice versa (the original shortest route was blocked by a barrier), an analysis of variance revealed significant main effects for the factors *age group*, $F(2, 48) = 7.81$, $p < .01$, $\eta^2 = .25$, *sex*, $F(1, 48) = 14.25$, $p < .01$, $\eta^2 = .23$, and *direction*, $F(1, 48) = 4.12$, $p < .05$, $\eta^2 = .08$. Younger children ($\bar{x} = 2233.85$ SU, $SE = 160.43$) walked longer distances than older ones ($\bar{x} = 1503.93$ SU, $SE = 255.89$) and adults ($\bar{x} = 1099.74$ SU, $SE = 160.43$), where only the difference between younger children and adults revealed statistical significance (Bonferroni adjusted; see Figure 5). The walked distance was shorter when walking from the start point to the objects ($\bar{x} = 1409.74$ SU, $SE = 182.44$) than vice versa ($\bar{x} = 1815.74$ SU, $SE = 169.89$). Furthermore, males walked shorter distances than females (males: $\bar{x} = 1164.41$ SU, $SE = 180.84$; females: $\bar{x} = 2060.61$ SU, $SE = 202.56$). Neither an effect of the factor *type of maze*, $F(1, 48) = 1.28$, *ns*, $\eta^2 = .03$, nor any significant interaction was found.

Phase 4: Survey knowledge task. Concerning the distance walked between objects a univariate analysis of variance revealed only a significant influence of the factors *age group*, $F(2, 48) = 3.87$, $p < .05$, $\eta^2 = .14$, and *sex*, $F(1, 48) = 7.59$, $p < .01$, $\eta^2 = .14$. Figure 5 shows that younger

($\bar{x} = 2294.11$ SU, $SE = 337.35$ SU) and older children ($\bar{x} = 2290.58$ SU, $SE = 566.89$ SU) walked longer distances than adults ($\bar{x} = 1050.70$ SU, $SE = 191.63$ SU), although the Bonferroni adjusted post hoc test did not reach a statistically significant level. Again males walked shorter distances ($\bar{x} = 1298.36$ SU, $SE = 237.72$ SU) than females ($\bar{x} = 2453.33$ SU, $SE = 390.50$ SU). The factor *type of maze*, $F(1, 48) = 3.14$, *ns*, $\eta^2 = .06$, did not influence the distance walked. There was neither a significant interaction between *age groups* and *sex*, $F(1, 48) = 1.37$, $\eta^2 = .07$, *age groups* and *type of maze*, $F(2, 48) = 1.16$, *ns*, $\eta^2 = .05$, and *sex* and *type of maze*, $F(1, 48) = 0.28$, $\eta^2 = .01$, nor a three-way interaction, $F(2, 48) = 2.71$, $\eta^2 = .1$.

DISCUSSION

The missing influence of the environmental structure

The main result of this study was that even with: (a) a self-determined, but controlled exploration phase; (b) fine-grained and multiple measurements to obtain subjects' spatial knowledge in much more detail and on an action basis to avoid complex cognitive transformations that are needed in, e.g., a map-drawing task; and (c) the variation of the environmental factor by the parallel manipulation of regularity *and* symmetry, the environmental structure did not reveal any significant influence on spatial knowledge. Because three different routes had to be learned, this result is independent of the characteristics of a specific route. The question arises as to whether participants had paid attention to the (ir)regularity of the spatial structure when walking through the virtual environment at all, and whether their mental representation mirrored the regularity versus irregularity of the environment. Otherwise, the lack of an effect would not be too surprising. Unfortunately, this question was not explicitly tested in the present study. However, the analysis of map drawings of an unpublished study with second graders, sixth graders, and adults, where the wayfinding performance and the spatial knowledge was investigated in exactly the same irregular and regular virtual environment, supports the assumption that the (ir)regularity of the virtual environment did indeed affect the (ir)regularity of the mental representation of the large-scale space. Independent of subjects' age, 80% of the subjects in the regular maze condition produced drawings that were symmetrical, whereas only 40% of the subjects in the irregular maze produced symmetrical drawings (Chi-square = 10.0, $p < .01$). These data certainly support the assumption that the (ir)regularity of the environment was not only recognized but mentally represented even in a desktop virtual-reality situation.

The missing influence of the regularity is in accordance with the study of Herman et al. (1987). Concerning the transfer of the geometric module hypotheses to studies in a large-scale space and the empirical investigation of the regularity hypotheses, we were not successful, because the regularity of the environment, as it is operationalized here, did not influence the spatial knowledge of children or adults. One possible reason is that with increasing age children might become more capable of regularizing irregular features, as has already been shown in spatial memory research with adults (Montello, 1991; Tversky, 2000). Bearing in mind that this was one of the first studies with children and adults investigating the influence of the environmental structure in large-scale space in a systematic manner, other studies have to be undertaken where: (a) the regularity of the environment would have to be varied in different ways; (b) the space would have to be manipulated from small- to large-scale space; (c) in addition to spatial-knowledge tasks, way-finding tasks would have to be used; and (d) children at different age groups (from 3 to 14 years) would have to be investigated. The validity of the geometric module/regularity hypotheses cannot be finally decided unless these studies are done. Unfortunately, our results do not allow us to decide if, in line with Piaget's view, the assumption that the configuration of the environment can not effect the spatial cognition of younger children holds true, because the variation of this structure did not influence the spatial knowledge of either the adults or the children.

The developmental perspective of the environmental structure

All measurements of spatial knowledge obtained here showed a significant difference between the performance of adults and younger children. The performance of the older children sometimes equalled that of the younger children (survey-knowledge task), took an intermediate position between younger children and adults (route-knowledge task, direction estimation task I, detour tasks), or was comparable to that of the adults (direction estimation task II). This is in accordance with other studies regarding spatial cognition measurements in an environmental space. For example, in a study by Cohen and Schuepfer (1980) it was shown that when finding their way in an unfamiliar environment, school-aged children relied on the presence of landmarks more than adults did, whereas second graders had more difficulties than sixth graders. In contrast to this, in two studies by Cornell and colleagues, the performance of 12-year-old children was similar to that of adults. Cornell, Heth, and Alberts (1994) did not find a difference between 12-year-old children and adults retracing a previously explored route, and both the children and adults used the instruction to look back to enhance their wayfinding performance (Cornell, Heth, & Rowat, 1992). This was not true for children of 8 years of age. Differences in age effects on spatial knowledge between studies might be due to the fact that the different tasks demand different capabilities, like a route-reversal task demands a mental-rotation performance in some way. The different capabilities, in turn, might develop differently with age (Allen, Kirasic, & Beard, 1989; Allen & Ondracek, 1995) and should be further investigated in more detail. But one point seems to be worth mentioning: Although we did not find a difference concerning the influence of the environmental structure for either adults or children, age differences were found in all measurements. It has to be discussed whether the development of spatial cognition might be more than a special case of cognitive development per se (compare Allen & Ondracek, 1995). Surely, significant developmental changes in spatial coding are not in fact completed in infancy but continue through school age (Newcombe & Huttenlocher, 2000), but this also holds true for other, non-spatial cognitive achievements.

Sex difference in spatial knowledge acquisition in a large-scale space

Interestingly, we found sex differences, which favoured males, in almost every measurement obtained. This finding can not be attributed to different configurational strategies since we found no type of maze and sex interaction. Additionally, because there was no difference in computer experience between males and females, the effect can not be traced back to the use of a desktop virtual environment in our study. The observed sex difference, however, is in line with the findings of Tlauka, Borlese, Pomeroy, and Hobbs (2005) and Moffat, Hampson, and Hatzipantelis (1998). The authors showed a male advantage in navigation in a virtual maze that could not be attributed to greater computer experience. It is even more interesting that we found sex differences in the group of younger children, because there is little agreement in the literature about whether the onset of sex differences on spatial cognition occurs before or after puberty. In a real-environment study with 1800 children of different age levels, Johnson and Meade (1987) showed that a male advantage in spatial cognition appears reliably by the age of 10 years, which is in line with the results of a study by Kerns and Berenbaum (1991). Our study is the first to show gender differences in a virtual environment not only for adults but also for school-age children, a finding in line with real-world studies.

The use of virtual environments

There were also two other interesting points regarding the use of virtual environments in spatial cognition developmental research: First, whereas the error in the first direction estimation task was very high (it varied between

$\bar{x} = 38.95°$ for adults and $\bar{x} = 65.15°$ for younger children), it was substantially lower in the second estimation task (it varied between $\bar{x} = 25.12°$ for adults and $\bar{x} = 44.71°$ for younger children). One reason might be that it is more difficult to estimate the direction between objects in the maze compared to estimating the direction from the objects to the start point or vice versa, a situation where the start point might serve as a reference point. But it could also be possible that performance in the estimation task improves with practice. It seems reasonable to investigate how spatial cognition gets more precise from one learning trial to the next one in a desktop virtual environment.

Second, the question of orientation specificity of spatial representations deserves to be investigated in more detail. Montello, Waller, Hegarty, and Richardson (2004) argued that viewing spaces from multiple perspectives during learning might eliminate alignment effects. Therefore, one might assume that spatial knowledge is stored orientation free (or in multiple orientations). In contrast, in our study the spatial information that was learned in the virtual environment turned out to be orientation specific, which is in line with a number of other studies (e.g., Albert, Rensink, & Beusmanns, 1999; Christou & Bülthoff, 1999; Richardson, Montello, & Hegarty, 1999). In the study of Richardson and colleagues, for example, the preferred orientation appears to be the one that is aligned with the initial view of the participant during learning. In accordance with this, in our study it turned out to be much easier for all participants to estimate the direction of the goal from the start point compared to estimating the direction from the goal object to the start point. The same orientation specificity was found in the more action-based measure of the distance walked. The control of the self-determined exploration could probably have led to the fact that participants did not represent multiple perspectives. Further studies are needed to clarify this aspect. It is worth remembering that in one direction estimation (phase 3) the orientation specificity was present only for females. That means that differential factors probably have to be taken into account.

Finally, we have to confirm that the use of virtual environments in developmental spatial cognition research seems to be appropriate for investigating spatial knowledge acquisition. Because navigation performance, for example, is simple to record in virtual reality experiments, spatial knowledge can be assessed more directly without recourse to complex mental transformations that depend, at least partly, on more general cognitive abilities. But these experiments can only complement, not replace, experiments in real environments. To be objective, the robustness of findings and the generalization using the desktop system has to be discussed, and studies have to be conducted to directly compare the knowledge acquisition in real and virtual environments under a developmental perspective. There is evidence from studies with adults that at least the most important properties of the spatial representations that underlie spatial behaviour can be analysed both in real and virtual environments (Loomis, Blascovich, & Beall, 1999), and that testing in virtual and real environments leads to similar outcomes (Péruch & Wilson, 2004; Tlauka, 2004). With the exception of one study (Plumert, Kearney, & Cremer, 2004), however, this comparison is still missing with children.

CONCLUSION

With this study, the first step was undertaken to investigate the influence of the environmental structure on spatial knowledge in an environmental space for both children and adults. The variation of the regularity of the environment did not have any influence on spatial knowledge. Even though this result is in accordance with Herman et al. (1987), many questions might be worth being addressed in more detail. These questions concern the influence of different forms of regularity variation and other geometric variations as has been found in studies of the geometric influence of room structure in younger children's reorientation performance.

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