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Reorientation in a rhombic environment: No evidence for an encapsulated geometric module

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Abstract

Reorientation behavior of young children has been described as dependent upon a geometric module that is incapable of interacting with landmark information. Whereas previous studies typically used rectangular spaces that provided geometric information about distance, we used a rhombic space that allowed us to explore the way children use geometric information about angles. Reorientation was studied in manipulatory space (Experiment 1) and locomotor space (Experiment 2) in the presence and absence of a salient landmark. In the absence of salient landmarks, 4- to 6-year-olds used geometric features to reorient in both spaces. When a salient landmark was available in manipulatory space, 4-year-olds used the landmark and ignored the geometry. Five- and 6-year-olds used the geometry, but in combination with the landmark. In locomotor space, this combined use was already seen at age 4, and increased with age. Taken together, these results offer no support for the notion that reorientation behavior in young children depends on an informationally encapsulated geometric module.

Keywords: Spatial orientation; Spatial memory; Cognitive development; Geometric module

Successful orientation in space is an essential ability, not only for humans but also for most mobile organisms. An important aspect of spatial orientation is reorientation, i.e., re-establishing one's own spatial heading and position after a period of disorientation. For instance, after getting off a rollercoaster, most people still find their way out of the fair-grounds. What cues do people and nonhuman animals use to orient and reorient themselves?

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Imagine a hungry rat in a familiar environment with a previously visited food source. Experience in, and exploration of, that environment had resulted in the creation of an internal cognitive map (O'Keefe & Nadel, 1978). A cognitive map is an absolute, nonegocentric, spatial representation of the environment that uniquely defines any given place by its distance and direction from distant landmarks. This cognitive map provides the rat with information about its own and the food's positions. It can be used to compute the egocentric position of the food such that the rat can successfully navigate towards it. However, when a rat is disoriented, it first needs to re-establish its own position relative to its surroundings (reorientation or map-alignment) before it can relocate the food. In that way, the places at which the rat searches for food are informative about the cues the rat uses to reorient itself.

Cheng (1986, see also Cheng & Gallistel, 1984) was among the first to study those aspects of the surroundings disoriented rats use to relocate places. Cheng studied rat's food searching behavior in an enclosed rectangular environment. The food's odor, the brightness of the walls and distinct panels in the corners served as distinctive landmarks. Without any distinctive landmarks, a rectangular space is rotational ambiguous because a target place cannot be distinguished from a place located at 180° rotation through the center of the environment. This is because the two diagonally opposite corners share the same combination of metric (longer–shorter) and sense (left–right) information. If a rat defines the food location only by its geometrical relation to the overall shape of the rectangular box, it could not differentiate between the two geometrically correct locations. This is exactly what Cheng found in his study. When trying to relocate a previously visited food source, disoriented rats systematically confused the two geometrically equivalent locations, although the correct location was unambiguously defined by the nongeometric landmarks (for similar findings see Biegler & Morris, 1993, 1996; Margules & Gallistel, 1988; for a more detailed discussion on rats' reorientation behavior, see Gallistel, 1990).

Cheng (1986) concluded that rats represent space in a modular fashion. When trying to relocate places after disorientation, rats rely dominantly on a "geometric module", which is defined as a featureless metric frame that "records the geometric relations in the arrangement of surfaces as surfaces" (Cheng, 1986, p. 175). According to this view, information about other features of the environment, such as landmarks, is processed in separate modules, and does not interact with geometric information when the animal is forced to reorient itself.

Since Cheng's (1986) finding, reorientation behavior has been studied in a variety of other vertebrates. Findings with birds, fish and monkeys show that these animals encode the geometric shape of an environment even when featural cues sufficiently specify target locations. However, not all species seem to share a reorientation mechanism that exclusively relies on geometric information. While chicks (Vallortigara, Zanforlin, & Pasti, 1990) use either only geometric or only nongeometric information depending on the specific task procedure, pigeons (Kelly, Spetch, & Heth, 1998), fishes (Sovrano, Bisazza, & Vallortigara, 2002, 2003), and rhesus monkeys (Gouteux, Thinus-Blanc, & Vauclair, 2001) conjoin geometric and nongeometric information to reorient themselves. This suggests that different species might use different types of information to relocate objects in space.

How do humans reorient in space? Following Cheng's (1986) logic, Hermer and Spelke (1994, 1996; see also Hermer-Vazquez, Moffet, & Munkholm, 2001; Hermer-Vazquez, Spelke, & Katsnelson, 1999) employed object retrieval tasks in order to find out which cues children and adults use to reorient themselves. Like Cheng, Hermer and Spelke used a rectangular environment (a 6.25 ft × 4.0 ft chamber). While the participant was watching, an object was hidden behind one of four identical corner panels. A disorientation procedure (rotation of the participant) followed after which the participant was asked to relocate the object. Participants were tested in an all-white chamber and in a chamber with one blue wall. In the rotationally ambiguous all-white chamber, participants cannot differentiate between the target corner and the diagonally opposite corner. Although adding a colored wall eliminates the rotational ambiguity of the apparatus, only subjects older than 4 years of age concentrated their searches in the correct corner. Two- to 4-year-olds in contrast neglected the color information. Behaving as they had in the all-white room, and as the rats in Cheng's experiments, they relied solely on geometry. The same result was observed using solid object landmarks such as a toy truck (but see Learmonth, Newcombe, & Huttenlocher, 2001 for contrasting results). The finding that young children's reorientation behavior seemed to be comparable to that of rats led Hermer and Spelke to suggest that humans share an informationally encapsulated shape-based reorientation system (geometric module) with other mammals. They suggested that spatial language is the mechanism through which the limits of the phylogenetically old system can be transcended, especially the production of the terms "left" and "right" (Hermer-Vazquez et al., 1999, 2001).

The assumption that the mind/brain consists of innately specified, domain-specific modules (input systems) that are informationally encapsulated and insensitive to higher cognitive processes goes back to Fodor (1983). Modules are said to underlie perceptual and other cognitive processes (e.g., language, face processing), and are assumed to form an infant's basic cognitive architecture from which further development progresses (for a critical review, see Karmiloff-Smith, 1992, 1994). As for the geometric reorientation module, one might question the evolutionary value of such a module. Obviously, animals have not evolved in enclosed geometric spaces. Hermer and Spelke (1996) argue that "reliance on geometric properties is likely to be adaptive in natural settings, where the macroscopic shape of the environment seldom changes, but where snowfall and melting, . . ., and other events frequently change the environment's nongeometric properties" (p. 198). Although this view is intuitively appealing, the distinction between geometric and nongeometric features is blurry, especially in natural settings. For instance, can a tree be characterized as a nongeometric landmark or does it contribute with its circumscribed geometric properties to the overall shape of the environment?

Almost all studies of reorientation behavior have used rectangular environments, which provide both metric (length) and sense (left–right) information. There are two exceptions. In a study by Gouteux and Spelke (2001) objects were hidden in an open circular space furnished with three to four salient landmarks. Three- to 4-year-olds used neither the nongeometric properties of the landmarks nor the distinctive geometric configuration formed by the landmarks to reorient themselves. The authors conclude that reorientation of young children critically depends on the shape of the surrounding surface layout (but see Huttenlocher & Vasilyeva, 2003). The other exception to the use of rectangular spaces is a recent study by Huttenlocher and Vasilyeva (2003) on reorientation in an isosceles triangle, in which 2-year-olds were able to use geometric information. Specifically, children used the relative lengths of adjacent walls in combination with sense information for reorientation. There was no condition with salient landmarks included in the study.

It is crucial to investigate the use of other kinds of geometrical information for reorientation and their possible combination with landmark information before accepting the existence of a dedicated and encapsulated geometric module that controls reorientation behavior in young children and rats. In the present study, we used a rhombic space, in which one typically relies on angular information to differentiate geometrically correct from geometrically incorrect places. A rhombus is geometrically ambiguous in that the two diagonally opposite corners share the same angular information. It is important to note that reorientation in a rhombic space does not necessarily rely upon angular information coding but can also be based on the calculation of the differences in the diagonal lengths (Newcombe, personal communication). However, children who gave meaningful data on how they solved the object retrieval task in our study explicitly referred to angular information. In any case, target locations cannot be differentiated from locations at 180° rotation through the center of the environment without taking additional nongeometric information into account. The purpose of the present study was to test (1) whether children can use angular information to reorient, and (2) whether geometry dominates reorientation behavior in young children in a rhombic space as some claim it does in rectangular spaces. In Experiment 1, we studied children's object retrieval behavior in a tabletop "manipulatory" apparatus. In Experiment 2, we tested whether the findings of Experiment 1 also held in a large "locomotor" space, within which the children moved.

1. Experiment 1

Gouteux, Vauclair, and Thinus-Blanc (2001) studied object retrieval behavior of 3- to 5-year-olds and adults in a rectangular tabletop apparatus. They found that the combined use of geometric and nongeometric (colored wall) information emerges at 5 years of age, which is later than in locomotor spaces. Other than this difference in time of emergence, they concluded that similar types of processing are implemented in manipulatory (tabletop) and locomotor space. One major procedural difference between a tabletop and locomotor space concerns the disorientation procedure. Subjects in locomotor spaces are spun around in order to lose their bearings. In contrast, in manipulatory spaces, subjects keep a stable position throughout the experiment. What is changed is the orientation of the apparatus with respect to the larger surrounding. Experiment 1 used a tabletop apparatus shaped like a rhombus and attempted to extend Gouteux, Vauclair, et al.'s result to the domain of "angle", a different geometric cue than the ones manipulated in prior work.

1.1. Method

1.1.1. Design and participants

A 2×3 mixed factorial design was used in Experiment 1. The variable that was manipulated within subjects was landmark information: Each child performed four trials with an apparatus in which all four walls were colored blue (no-landmark condition) and four trials with the same apparatus but a red cardboard attached to one of the walls (landmark condition). The number of trials (four) administered was based on previous studies (e.g., Hermer & Spelke, 1996). The order of trial blocks (landmark versus no-landmark condition) was quasi-randomized across children such that half of the children in each age group performed the four trials of the landmark condition first and then the four trials of the no-landmark condition, whereas the other half of the children followed the opposite order. The between-subjects variable was age group. Sixteen 4-year-olds (12 females, 4 males, mean age = 4 years, 6 months; range = 4 years, 0 month to 4 years, 11 months), sixteen 5-year-olds (6 females, 10 males, mean age = 5 years, 6 months; range = 5 years, 0 month to 5 years, 11 months), and fourteen 6-year-olds (6 females, 8 males, mean age = 6 years, 7 months; range = 6 years, 6 months to 7 years, 3 months) participated in the experiment. Written parental consent was obtained from parents of all children who participated in the present experiment prior to the study.

1.1.2. Material

The tabletop apparatus (84 cm × 84 cm × 14 cm) was made of wooden panels painted light blue. The ground shape of the apparatus was rhombic. Two corners were 60°, and the other two corners were 120° wide. Four identical opaque plastic containers with removable lids were placed in the four corners of the apparatus (see Fig. 1). The apparatus contained no other salient landmarks. Therefore, it was impossible to distinguish the two diagonally opposite corners from each other in the all-blue apparatus. A little plastic toy figure was used as the hiding object. A piece of red cardboard was attached to the inside of one of the walls for the landmark condition. Because the apparatus was positioned at the height of the children's waistline, the red cardboard was visible for the children at all times. While the red cardboard held a stable position within the apparatus, it changed its position in relation to the child throughout the experiment due to the rotation of the apparatus. The apparatus sat on a turnable disk on a stool with the bottom of the apparatus completely covering the stool. The experiment took place either in a room at a daycare facility with several different objects located around the apparatus (tables, chairs, toys, plants, etc.) or in a room at the University with several pictures on the walls. In both rooms, there was enough empty space around the apparatus such that the experimenter and the child could freely move and rotate the apparatus.

1.2. Procedure

1.2.1. General procedure for the object retrieval task

The experiment was introduced to the child as a "hide and seek" game. The experimenter showed the child the apparatus and encouraged the child to open all four boxes to ensure that they were empty at the beginning of the experiment. Then the experimenter explained the game. The child was told that a plastic toy would be hidden in one of the four boxes and that s/he should try to remember the hiding location, because later s/he would be asked to retrieve the toy. After hiding the toy, the experimenter rotated the apparatus 450° clockwise or counterclockwise such that the new position differed from the original position 90°. The same rotation procedure was used by Gouteux, Vauclair, et al. (2001). It was chosen instead of a complete random one, because it ensured that the apparatus appeared in a visibly different position during retrieval and hiding. So even when the children did not watch the rotation of the apparatus (invisible rotation trials, see below), the apparatus' position change was obvious for the children. This should encourage children to use allocentric (viewer-independent) coding strategies.

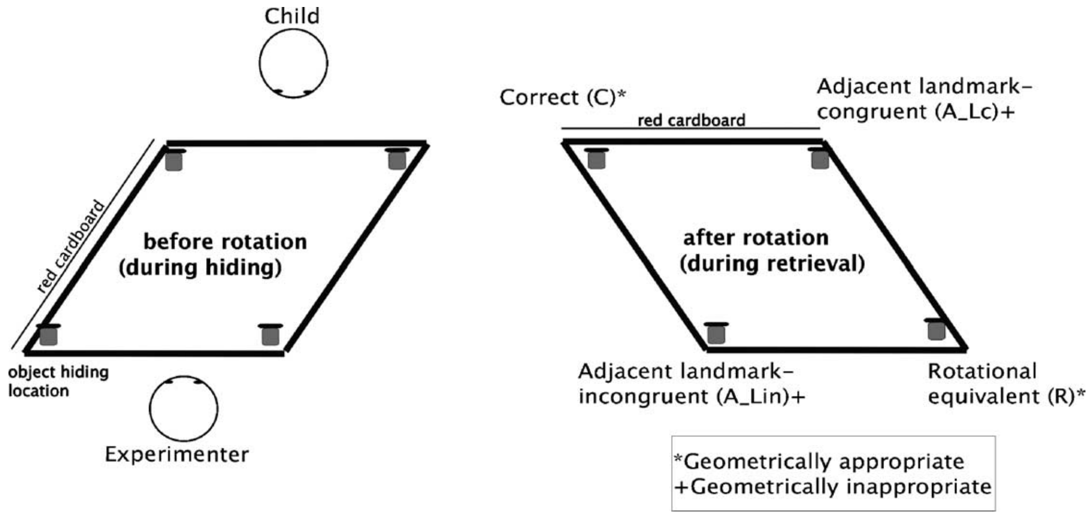

Fig. 1. Apparatus used in Experiment 1. Depicted is the landmark condition, in which a red cardboard was attached to one of the walls. The right side of the figure shows the labels for the different search locations. In contrast to the landmark condition, the two geometrically inappropriate corners were not further specified in the no-landmark condition. Note that for each child, all four corners were used as hiding locations once throughout the four trials of each condition (landmark and no-landmark condition).

After the rotation of the apparatus, the child was asked to retrieve the toy. For all trials, the child was allowed only one retrieval attempt, because a pilot study suggested that children tried harder when they were not allowed to search until they had found the toy. The first time the child successfully retrieved the toy, the experimenter explained that every time the child retrieved the toy, s/he would be allowed to put a plastic block into a container, and that the blocks would be counted at the end of the experiment to determine if the child should receive a prize. If the child did not correctly remember the hiding location, the experimenter retrieved the toy while the child was watching. The next hide/search trial followed immediately. The procedure continued until all trials of one condition (landmark versus no-landmark) were administered. After the first condition, the experimenter either removed or attached the red cardboard while the child was watching. The experimenter simply announced that the apparatus was going to change a little bit but that the rules of the game would stay the same.

1.2.2. Visible rotation trials

During the first two trials, children watched as the experimenter rotated the apparatus, with or without a landmark depending on which group the child was assigned to (landmark condition first, or no-landmark condition first). The object was hidden once in one of the acute-angled corners, and once in one of the obtuse-angled corners. In one of the trials, the apparatus was rotated clockwise, and in the other trial, it was rotated counterclockwise (the order was randomized across children). The visible rotation trials were included in order to minimize egocentric coding attempts (such as "the hiding location is on my left side in the front") by showing the child that the actual hiding location "moved" with the apparatus.

1.2.3. Invisible rotation trials

After the visible rotation trials, the experimenter explained that the game would get more difficult, because the child would no longer be allowed to watch the rotation process. After the object had been hidden, the child was asked to close his/her eyes while the experimenter rotated the apparatus. Additionally, the child was asked to face the room wall to prevent him/her from cheating. As in the study by Gouteux, Vauclair, et al. (2001), across the four trials in the no-landmark and the landmark condition all four possible hiding locations were used once, i.e., the toy was hidden at a different place each time. The order of locations was randomized. This manipulation was used instead of a complete random sequence in order to avoid the possibility that one specific hiding location would by chance be used more frequently than other locations, because this could have led children to assume that a stable hiding location was being used.[1]

Additionally, for each condition (landmark versus no-landmark), the apparatus was rotated clockwise for half of the trials, and counterclockwise for the other half of the trials. After the apparatus sat in its final position, the child was asked to open his/her eyes and to find the toy.

[1] Our manipulation could have led children to adopt a strategy of avoiding previous hiding locations. However, this would require children to correctly remember previous hiding locations. This does not only seem to be a much more difficult/sophisticated strategy than simply focusing on the current hiding location, it should also lead to decreasing error rates with increasing trials (simply because the more hiding locations were used before the less the amount of possible hiding locations in a given trial). This was not revealed by the data.

1.2.4. Spatial language production and comprehension test

After the first block of invisible rotation trials, all children performed a spatial language production and comprehension test. This test was modeled after Hermer-Vazquez et al. (2001). Because Hermer-Vazquez et al. showed that the use of the terms "left" and "right" plays a crucial role in flexible reorientation, the spatial language tests focused on the production and comprehension of these terms. First, the *production test* was administered. The child and a second experimenter[2] sat on different tables facing opposite directions. A set of two different colored plastic blocks (a blue and a red one) was placed in front of the child, and a second set of these blocks was placed in front of the second experimenter. The child was asked to describe the arrangement of the blocks such that the second experimenter could arrange her set in the same way. The test always started with an example trial in which the first experimenter put the blue block on top of the red one and verbally described the arrangement. Seven trials followed, in which the blue block was placed twice on the right, and twice on the left side of the red block, and once under, once behind and once in front of it. The order of arrangements was quasi-randomized such that the same arrangement did not occur twice in a row. For each trial the experimenter asked "Where is the blue block in terms of the red one?" The experimenter did not give any feedback. If children did not respond, the experimenter repeated the example. Immediately after the production test, the *comprehension test* followed. Now the first experimenter described the arrangement of the blocks and the child was asked to carry it out (e.g., "Put the blue block in front of the red one"). Eight trials (right and left twice, top, under, front and behind once) were again administered in quasi-random order. No feedback was given. After the comprehension test, the second block of four invisible rotation trials followed, using the other condition (landmark versus no-landmark).

At the end of the experiment, the child was allowed to choose a small gift out of a gift box regardless of how successful the child was in the object retrieval task.

1.3. Results

Fig. 1 shows the different corner labels referred to in the following section. The correct corner refers to the actual hiding location. The rotational equivalent corner refers to the diagonally opposite corner, which shares the angular information with the correct corner, and hence, cannot be differentiated from the correct corner in the no-landmark condition. Therefore, both the correct and the diagonally opposite corner are geometrically appropriate search locations. The other two corners that are adjacent to the correct corner are geometrically inappropriate search locations, because they differ geometrically from the correct location. In the landmark condition, we can additionally differentiate between the two corners that share a wall with the correct corner (the "adjacent" corners). One of them shares the landmark with the correct hiding location (adjacent landmark-congruent corner), while the other does not (adjacent landmark-incongruent corner).

The significance level for all the results of this and the following experiment was set at $\alpha = .05$. Fig. 2 depicts the mean search frequencies at each corner for each age group and condition (averaged over all four invisible rotation trials).

[2] Children who were seen at the University laboratory performed the production test with their mothers/fathers.

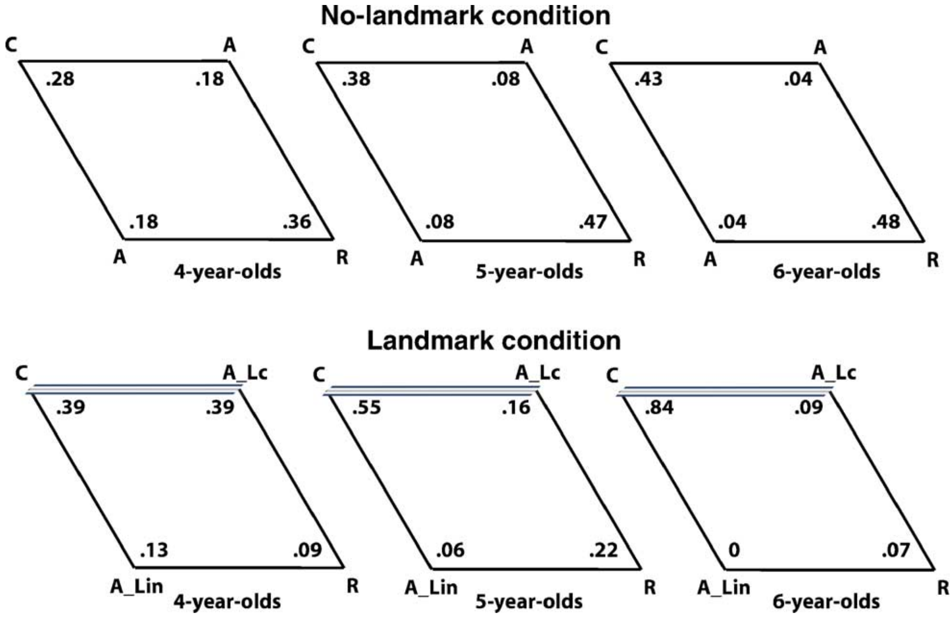

Fig. 2. Mean search frequencies at each corner in each age group and condition (landmark vs. no-landmark) in the tabletop apparatus (averaged over all four invisible rotation trials).

In the visible rotation trials, we expected children of all age groups to search correctly, because no reorientation was necessary. In line with our expectation, only one 4-year-old searched at incorrect corners on both trials. Seven 4-year-olds, one 5-year-old, and two 6-year-olds searched at an incorrect location in one of the trials.

The invisible rotation trials were analyzed in the following way. For both the landmark and the no-landmark condition, we first analyzed the "geometric" search patterns, i.e., the mean search frequencies for the two geometrically appropriate corners (the correct and the rotational equivalent corner). In the all-blue-wall apparatus (no-landmark condition), no differences in search frequencies between the two corners were expected in any of the age groups, because the apparatus provided no means for differentiating between these two geometrically identical corners. The assumption of a geometric module implies that the use of geometric information is innate or at least functional very early in life. Therefore, we expected that children of all ages would be able to use the angular information and would search geometrically appropriate corners more frequently than geometrically inappropriate corners in the no-landmark condition. To test this hypothesis, we additionally compared the mean search frequencies for the two geometrically appropriate corners with the mean search frequencies for the two geometrically inappropriate corners for each age group separately.

In the landmark condition, we also first analyzed the "geometric" search patterns. In this condition, it was possible to further disentangle the two geometrically identical corners by relying on the position of the red cardboard. Based on previous findings (e.g., Hermer-Vazquez et al., 2001), we expected children above the age of 5 years to make use of the red cardboard and to search the correct corner more frequently than the rotational equivalent corner. In contrast, younger children's reorientation system is assumed to depend upon a geometric module incapable of incorporating landmark information. Based on this assumption, children younger than 5 years of age should continue to search the two geometrically adequate corners equally often.

For the landmark condition, we were not only interested in the "geometric" search patterns, but also in the "nongeometric" search patterns. Therefore, we compared mean search frequencies at the two landmark-congruent corners (i.e., the correct corner and the adjacent landmark-congruent, but differently shaped corner). We hypothesized that children of all ages would search the correct corner more often than the adjacent landmark-congruent corner, because none of the age groups was expected to solely rely on landmark information. Because older but not younger children should be able to combine geometric and landmark information, we additionally expected to find an age group by corner interaction: While older children should search the correct corner more frequently than younger children, no difference between age groups was expected for the adjacent landmark-congruent corner.

Two kinds of systematic errors can be differentiated in the landmark condition. (1) Children could ignore the landmark information, and solely rely on angular information. In this case, we would expect children to confuse the two corners that share the same angular information (i.e., the correct and rotational equivalent corner). (2) Children could ignore the geometrical information, and rely only on landmark information. In this case we would expect children to confuse the two landmark-congruent corners (i.e., the correct and the adjacent landmark-congruent corner). We will refer to these two kinds of errors as geometrical and landmark errors, respectively. In order to analyze whether the children in the different age groups made more geometrical or landmark errors, mean search frequencies at the rotationally equivalent corner were compared to mean search frequencies at the adjacent landmark-congruent corner for each age group separately. Because of the dominant use of geometric information, children younger than 5 years of age should commit more geometrical than landmark errors. No difference was expected for older children who were expected to make generally fewer and random errors.

At the end of the results section, we report the correlations between the searches at the correct corner in the landmark condition and the production and comprehension of the terms "left" and "right". Based on the finding of Hermer-Vazquez et al. (1999, 2001) that flexible reorientation using landmark and geometric information critically depends on the production of these terms, we expected that correct searches in the landmark condition would positively correlate with successful production but not comprehension of the terms "left" and "right".

1.3.1. No-landmark condition

We analyzed the "geometric" search patterns in the all-blue wall apparatus (no-landmark condition) with a 3 (age group) × 2 (order: no-landmark condition first versus second) × 2 (corner: correct versus rotational equivalent) mixed analysis of variance (ANOVA) with mean search frequencies as the dependent variable. The analysis revealed a significant effect of age group [$F(2,40) = 10.56$, MSE = 0.01, $p < .01$] and a marginally significant effect of order [$F(2,40) = 3.23$, MSE = 0.01, $p = .08$]. Children who performed the landmark condition first searched the geometrically appropriate corners slightly more often ($M = 0.84$) than children who started with the no-landmark condition ($M = 0.74$). All other effects were not statistically significant [$F \leq 1.91$, $p \geq .16$]. The nonsignificance of the corner effect shows that children were not able to distinguish the correct hiding location from the diagonally opposite corner. This proves that our apparatus was indeed rotational ambiguous as intended. Multiple post hoc comparisons (Scheffé) for the age group effect showed that – somewhat surprisingly – 4-year-olds searched geometrically appropriate corners less often than 5- and 6-year-olds. Five- and 6-year-olds did not differ in their searching behavior.

In order to assess whether all age groups used geometric information in the no-landmark condition, mean search frequencies at geometrically appropriate corners were compared to mean search frequencies at geometrically inappropriate corners for each age group separately with paired-samples *t*-tests. As expected, all age groups searched at geometrically appropriate corners more frequently than at geometrically inappropriate corners [$t \geq 3.09$, $p < .01$].

Taken together, the analyses for the no-landmark condition showed that (1) children could not distinguish between the correct and the other same-angle corner, thus proving that the apparatus was rotational ambiguous, (2) previous experience with the landmark condition slightly facilitated geometric search behavior in the no-landmark condition, (3) children of all ages relied on geometry, i.e., they searched geometrically appropriate corners more often than geometrically inappropriate corners, and (4) the ability to rely on geometry improved with age.

1.3.2. Landmark condition

The "geometric" search patterns in the red-wall apparatus (*landmark condition*) were analyzed with a 3 (age group) × 2 (order: no-landmark condition first versus second) × 2 (corner: correct versus rotational equivalent) mixed ANOVA with mean search frequencies as the dependent variable. The analysis revealed main effects of age [$F(2,40) = 13.05$, $MSE = 0.03$, $p < .01$], corner [$F(1,40) = 4.96$, $MSE = 0.08$, $p < .01$], and significant interactions between age group and order [$F(2,40) = 3.33$, $MSE = 0.03$, $p = .05$], age group and corner [$F(2,40) = 6.80$, $MSE = 0.08$, $p < .01$], and a marginally significant interaction between order and corner [$F(1,40) = 3.80$, $MSE = 0.08$, $p = .06$, all other effects $F \leq 1.14$, $p \geq .33$].

Because we had no specific hypotheses about the interactions involving the order effect, we further analyzed only the simple effects for the age group by corner interaction. The analysis showed that age groups differed in their search frequencies at both the correct [$F(2,40) = 6.80$, $MSE = 0.08$, $p < .01$] and the rotational equivalent corner [$F(2,40) = 13.05$, $MSE = 0.03$, $p < .01$]. As expected, we found an age group-related increase in search frequencies at the correct corner. Search frequencies at the rotationally equivalent corner unexpectedly followed an inverted U-shaped function in dependence on the age group. Additionally, children in all age groups searched at the correct corner more often than at the rotationally equivalent corner [$F \geq 8.60$, $p < .01$], a pattern unexpected at least for the 4-year-olds.[3]

[3] Additionally, we directly compared the "geometric" search patterns for the landmark and the no-landmark condition with a 3 (age group) × 2 (order: no-landmark condition first vs. second) × 2 (corner: correct vs. rotational equivalent) × 2 (apparatus: landmark vs. no-landmark) mixed ANOVA. The most important result was a three-way interaction between age group, corner and apparatus [$F(2,40) = 3.29$, $MSE = 0.07$, $p < .05$]. Further analyses of the interaction confirmed the results of the separate analyses.

The “nongeometric” search patterns in the red-wall apparatus (*landmark condition*) were analyzed with a 3 (age group) × 2 (order: landmark condition first versus second) × 2 (corner: correct versus adjacent landmark-congruent) mixed ANOVA with mean search frequencies as the dependent variable. The analysis revealed significant main effects of age [$F(2,40) = 3.58$, MSE = 0.03, $p = .04$], and corner [$F(1,40) = 36.09$, MSE = 0.09, $p < .01$], a marginally significant effect of order [$F(2,40) = 3.59$, MSE = 0.03, $p = .07$], and a significant interaction between age group and corner [$F(2,40) = 11.36$, MSE = 0.09, $p < .01$]. Children who performed the no-landmark condition first [$M = 0.86$] searched at landmark-congruent corners slightly more often than children who started with the landmark condition [$M = 0.74$]. An analysis of the simple effects for the age group by corner interaction showed that age groups significantly differed in their search frequencies at both the correct [$F(2,40) = 9.96$, MSE = 0.08, $p < .01$] and the adjacent landmark-congruent corner [$F(2,40) = 8.57$, MSE = 0.04, $p < .01$]. Search frequencies at the correct corner increased with age, but search frequencies at the adjacent landmark-congruent corner decreased with age (see Fig. 2). While 5- and 6-year-olds searched the correct corner significantly more often than the adjacent landmark-congruent corner [$F(1,43) = 13.77$ versus $F(1,43) = 44.43$, respectively, MSE = 0.09, $p < .01$], we were surprised to find that 4-year-olds did not differentiate between the correct and the adjacent landmark-congruent corner [$F < 1$].

In order to analyze whether the children in the different age groups made more geometrical or landmark errors, mean search frequencies at the rotationally equivalent corner were compared to mean search frequencies at the adjacent landmark-congruent corner for each age group separately with paired-samples *t*-tests. In contrast to what we had expected, 4-year-olds searched significantly more often at the adjacent landmark-congruent corner than at the rotational equivalent corner [$t(15) = 3.14$, $p < .01$]. As predicted, search rates did not differ significantly between the two corners for 5- and 6-year-olds [$t < 1$].

Taken together, the analyses for the landmark condition revealed that (1) all children searched the correct corner more often than the rotational equivalent corner, (2) 5- and 6-year-olds additionally searched the correct corner more often that the adjacent landmark-congruent but differently shaped corner, whereas 4-year-olds systematically confused these two corners, (3) previous experience with the no-landmark condition slightly facilitated nongeometric search behavior in the landmark condition, and (4) 4-year-olds committed more landmark than geometric errors, whereas no difference between error types were observed for 5- and 6-year-olds. In line with our hypotheses, 5- and 6-year olds incorporated geometric and landmark information. Contrary to our expectation of a dominant use of geometric information, 4-year-olds ignored geometry and only used landmark information.

1.3.3. Spatial language production and comprehension

Additionally, we analyzed the correlations between successful search behavior in the landmark condition and the successful production and comprehension of the terms “left” and “right”. Scores for successful production and comprehension each varied from 0 to 4. A score of 4 means that a child successfully produced or comprehended the terms “left” in two trials and the term “right” in the other two trials. Performance in the landmark condition was significantly correlated with production of the terms “left” and “right” [$r = .39$, $p < .01$], but was not correlated with comprehension [$r = -.07$, $p = .64$]. Because age (in months) was also correlated with successful performance in the landmark condition [$r = .57$, $p < .01$], we analyzed the correlation between left–right production and successful search again with a partial correlation controlling for the effect of age. The correlation between left–right production and successful search dropped to $r = .24$, which was no longer significant [$p = .11$]. Correlations between successful searches in the landmark condition and production or comprehension of the other spatial terms were not significant [$r \leq .20$, $p \geq .18$].

1.4. Discussion

In Experiment 1 we studied children's object retrieval behavior in a rhombic tabletop apparatus with and without a salient landmark. As hypothesized, all children searched at geometrically correct locations more often than at geometrically incorrect locations in the no-landmark condition. This geometry-based search behavior improved with age (see also Gouteux, Vauclair, et al., 2001).

In the landmark condition, all children searched at the correct corner more frequently than at the rotational equivalent corner, thus *not* confusing the two geometrically identical corners. This was unpredicted at least for the 4-year-olds who were expected to ignore the landmark information. The detected pattern, however, does not mean that all age groups were able to combine geometric and nongeometric information successfully. The analysis of the nongeometric search patterns revealed that 5- and 6-year-olds, but not 4-year-olds searched the correct corner significantly more often than the adjacent landmark-congruent corner. Moreover, the analysis of the error rates showed that 4-year-olds committed significantly more landmark than geometrical errors. In sum, the results of the landmark condition showed that 5- and 6-year-olds successfully relied on both geometric and nongeometric information, whereas 4-year-olds neglected geometric information and solely depended on the salient landmark.

As in previous studies with locomotor spaces (Hermer-Vazquez et al., 1999, 2001), successful search behavior in the red-wall apparatus was correlated with the production of the spatial terms "left" and "right", but not with the comprehension of those terms. However, when we controlled for age the correlation was no longer significant. Since only correlational studies have been conducted so far, it remains unclear whether spatial language causes more flexible reorientation or whether both abilities simply emerge around the same age. Given these limits on interpretation, we did not include the spatial production and comprehension test in Experiment 2.

Our finding that 4-year-olds depended solely on nongeometric information stands in direct contrast to what has been reported for rectangular-shaped, locomotor spaces. Proponents of the geometric module claim that geometric information dominates reorientation behavior until nongeometric information can be incorporated in a flexible way around 6 years of age. A closer look at the Gouteux, Vauclair, et al.'s study (2001), which also used a tabletop apparatus, reveals interesting similarities to our results: Four-year-olds in their study confused the two landmark-congruent corners as did 4-year-olds in our experiment. Gouteux, Vauclair, et al. interpreted this dominant use of nongeometric information as reflecting a transition phase between the early neglect of nongeometric information and the later emerging combined use of geometric and nongeometric information. However, reorientation studies in navigable spaces do not provide evidence for such a transition phase.

What produces these different results in locomotor and manipulatory spaces? It could be the case that results in both spaces reflect a general limit in processing capacities of young children. For instance, in location coding tasks in homogeneous spaces (i.e., circles) children younger than 9 years of age show categorical coding only along one dimension (i.e., along the radial, but not the angular dimension) while older children and adults code locations categorically along both dimensions (Sandberg, Huttenlocher, & Newcombe, 1996). Sandberg (2000) showed that young children's deficits are due to limited encoding and/or processing capacities rather than to limited spatial abilities. Limited processing capacities could also explain why 4-year-olds in Gouteux, Vauclair, et al.'s and our experiment did not simultaneously use geometric and nongeometric information, although they could use both kinds of sources separately. The salience of features might determine which information will be used in a specific task. Nongeometric information might be more salient in manipulatory spaces, while in locomotor spaces, by contrast, geometric information might be the most salient feature.

In addition to a problem with limited processing capacities, the discrepant results between manipulatory and locomotor spaces might stem from the different "disorientation" procedures used in these two spaces. In locomotor spaces, the subject is spun around, whereas in manipulatory spaces, the apparatus' orientation is changed with respect to the larger surrounding. We and others (e.g., Gouteux, Vauclair, et al., 2001) nevertheless assume that similar spatial strategies are used in both spaces. In order to find the hidden object in manipulatory spaces, subjects could either mentally rotate the apparatus/themselves in order to re-establish their original (egocentric) position relative to the apparatus, or they could use a viewer-independent (allocentric) coding strategy by focusing solely on the hiding location's geometrical (and nongeometrical) properties. Similarly, after subjects are spun around in the locomotor space, they could either rotate themselves until they re-established their original heading direction, or they could use the allocentric coordinates of the location in order to retrieve the object. Huttenlocher and Vasilyeva (2003) have shown that children most likely employ the latter strategy.

To further explore similarities and differences between locomotor and manipulatory spaces, Experiment 2 asked how children behave in a rhombic space that is navigable. Will geometry dominate reorientation behavior of young children in a locomotor space when the crucial geometric information is angular?

2. Experiment 2

Experiment 2 was designed to replicate Experiment 1 in a locomotor space. Because previous studies repeatedly demonstrated geometric dominance in the reorientation behavior of children even younger than 4 years of age, we included 2- and 3-year-olds in addition to 4- to 6-year-old children in this study.

2.1. Method

2.1.1. Design and participants

A 5 × 2 mixed factorial design was used in Experiment 2. The within-subjects variable was landmark information: Each child performed four trials in an apparatus in which all four walls were colored blue (no-landmark condition) and four trials in the same apparatus but with one of the walls colored yellow (landmark condition). The order of trial blocks (landmark versus no-landmark condition) was quasi-randomized across children such that half of the children in each age group performed the four trials of the landmark condition first and then the four trials of the no-landmark condition, whereas the other half of the children followed the opposite order. The between-subjects variable was age group. Different children were recruited for Experiments 1 and 2. The final sample size included seven 2-year-olds (4 females, 3 males, mean age = 2 years, 9 months; range = 2 years, 6 months to 2 years, 11 months), fourteen 3-year-olds (8 females, 6 males, mean age = 3 years, 3 months; range = 3 years, 0 month to 3 years, 11 months), fourteen 4-year-olds (5 females, 9 males, mean age = 4 years, 6 months; range = 4 years, 0 month to 4 years, 11 months), fourteen 5-year-olds (7 females, 7 males, mean age = 5 years, 4 months; range = 5 years, 0 month to 5 years, 10 months), fourteen 6-year-olds (5 females, 9 males, mean age = 6 years, 6 months; range = 6 years, 0 month to 6 years, 11 months). This final sample size does not include children who (1) refused to close their eyes during the disorientation procedure or tried other ways to stay oriented while spinning on the sit'n spin and/or (2) performed less than two trials in one of the two conditions. By applying this criterion, we discarded data of two 2-year-olds, two 3-year-olds, one 4-year-old, and one 5-year-old from the final sample size. The sample size for the 2-year-old group was smaller than that for all other age groups, because the recruitment of 2-year-olds was stopped when preliminary analyses revealed that 3-year-olds searched randomly.

2.1.2. Material

The layout of the experimental room is depicted in Fig. 3. The experimental apparatus consisted of a 7 ft × 7 ft chamber with the ground shape of a rhombus. As in the tabletop apparatus, the acute angles were each 60° wide, and the obtuse angles were each 120° wide. The walls of the apparatus consisted of a lightweight metal frame covered with featureless blue fabric. The walls were connected to each other by hinges that could be opened and closed from outside. One corner of the room served as the entrance point. For the landmark condition, one wall was completely covered with a yellow curtain. Four purple cups were used as hiding containers. They were placed upside down in each corner touching the two walls forming the corner. A red plastic block was used as the hiding object. The apparatus itself was located in 11 ft × 11 ft square room. The walls of the square room were covered with featureless gray fabric. The roof consisted of light-diffusing featureless fabric. Indirect lighting came from above the ceiling curtain and was provided by four lamps attached to the ceiling an equal distance from the corners of the experimental apparatus. The square room was part of a bigger rectangular shaped laboratory space within a large University building.

2.2. Procedure

At the beginning of the experiment, the child listened to a 10-min tape of a children's story in the laboratory space outside the square room containing the experimental apparatus. The story was part of a different experiment on memory development. After listening to the story, children were invited to play a "hide and seek" game with the experimenter. Then the child and the experimenter entered the apparatus.

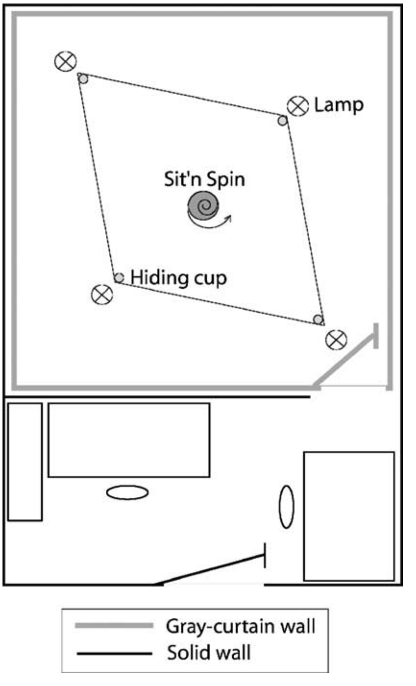

Fig. 3. Experimental apparatus used in Experiment 2.

2.2.1. Sit'n spin practice trial

First, the child was introduced to the sit'n spin and encouraged to practice spinning. For children who did not want to use the sit'n spin, or were not able to spin themselves around or did not want to perform the experiment without his/her mother/father, the parent was asked to help with the experiment. Six 2-year-olds and eight 3-year-olds performed the experiment with their mothers/fathers. Parents who accompanied their children during the experiment were instructed (1) to close their eyes while the experimenter hid the object so they would not know the hiding location and would therefore not be tempted to help the child, (2) to walk around in circles with the experimenter while the child was spinning on the sit'n spin, or to pick the child up and spin him/her around in case the child would not want to use the sit'n spin. For children who did not use the sit'n spin for disorientation, the sit'n spin was removed from the apparatus.

2.2.2. First block of object retrieval trials

After the child had decided whether to keep or remove the sit'n spin and/or whether to be accompanied by the parent, the second experimenter closed the apparatus from outside. The child was asked to look into all four cups to ensure they were all empty at the beginning of the experiment. Then the experimenter explained the "game". The child was told that the experimenter would hide a red plastic block under one of the cups and that the child would later be asked to remember the hiding location. After the experimenter hid the block under one of the cups, the child spun on the sit'n spin with his/her eyes closed or was picked up by the parent and spun around with his/her eyes closed. While the child was spinning, the experimenter (and the parent) walked around in circles in the direction opposite to that of the child. After approximately 10 s, the experimenter stopped the child by touching his/her shoulders. For every trial, the child was stopped at a predefined facing direction such that each wall was faced once in the landmark and no-landmark condition. The sequence of facing directions was randomized for each child. When the experimenter stopped the child, she always stood behind the child facing the same direction as the child. Parents who accompanied their children were instructed to stand next to the experimenter looking at the child at the time the child was stopped as well as during the time the child searched for the hidden object. The child got up the sit'n spin and was asked to find the red block. In each trial, the child was allowed only one attempt to retrieve the block. The first time the child successfully relocated the block, the experimenter explained the "reward system". Every time the child would choose the correct location, s/he would receive a sticker point. At the end of the experiment the points would be counted, and depending on the number of points gathered, the child would receive a gift. When the child searched incorrectly, the experimenter retrieved the block while the child was watching. Immediately after that, the next trial started. Across the four trials in the no-landmark and the landmark condition all four possible hiding locations were used once, i.e., the toy was hidden at a different place each time (see Experiment 1 for the rationale behind this procedure). The order of locations was randomized. The procedure continued until all four trials of the fist block were administered.

2.2.3. Filler task

After the first block of object retrieval trials, all children were brought outside the apparatus and sat down at the desk in the adjacent office space (see Fig. 3). The experimenter asked several questions about the story the children had heard at the beginning of the experiment. This task took about 5 min. During this time, the second experimenter prepared the apparatus for the next block of trials (i.e., she removed or attached the yellow sheet to one of the walls of the apparatus).

2.2.4. Second block of object retrieval trials

After the filler task, children returned to the apparatus and the next block of trials was administered (for children who started with the landmark condition, the no-landmark condition was administered and vice versa). At the beginning of the second block the experimenter pointed out that the yellow curtain was removed or added.

After the second block of search trials, children were again asked several questions about the story they had listened to in the beginning of the experiment. After that and regardless of the number of points earned during the spatial search task, the child received a small gift.

2.3. Results

Fig. 4 depicts the mean search frequencies at each corner for each age group and condition (averaged over all four trials in each condition).

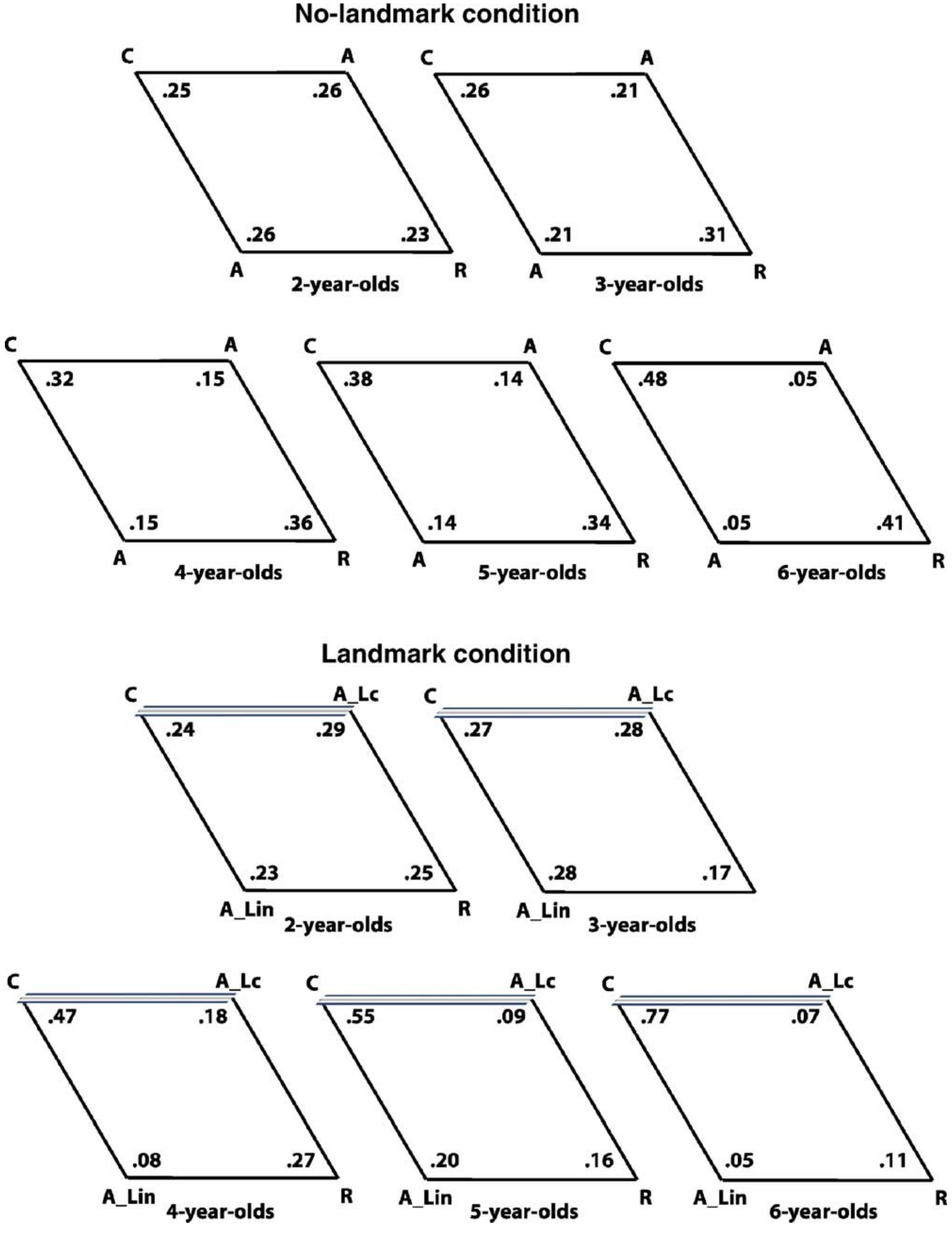

Fig. 4. Mean search frequencies at each corner in each age group and condition (landmark vs. no-landmark) in the locomotor space (averaged over all four trials).

The mean search frequencies were analyzed in the same way as in Experiment 1. Because the predictions for Experiment 1 were based on previous findings in locomotor spaces, the predictions for Experiments 1 and 2 are identical (for a detailed description of the predictions, see Section 1.3). The two younger age groups (2- and 3-year-olds) were expected to show the same pattern as predicted for the 4-year-olds, i.e., they should rely on geometric information, while neglecting additional landmark cues.

2.3.1. No-landmark condition

We analyzed the “geometric” search patterns in the all-blue room (*no-landmark condition*) with a 5 (age group) × 2 (order: no-landmark condition first versus second) × 2 (corner: correct versus rotational equivalent) mixed analysis of variance (ANOVA) with mean search frequencies as the dependent variable. The analysis revealed a significant effect of age group [$F(4,53) = 3.87$, MSE = 0.04, $p < .01$]. All other effects were not statistically significant [$F < 1$].

In order to assess which age groups used geometric information in the no-landmark condition, mean search frequencies at geometrically appropriate corners were compared to mean search frequencies at geometrically inappropriate corners for each age group separately with paired-samples *t*-tests. Only 4-, 5-, and 6-year-olds searched geometrically appropriate corners more often than geometrically inappropriate corners [$t \geq 2.40$, $p \leq .03$]. There was no difference in search frequencies between the geometrically appropriate and inappropriate corners for 2- and 3-year-olds [$t < 1$].

Taken together, the analyses of the no-landmark condition revealed that (1) children could not differentiate between the correct hiding location and the diagonally opposite location, thus showing that the apparatus was rotational ambiguous as intended, (2) children 4 years of age and older used the angular information to reorient themselves, whereas, unexpectedly, children below the age of 4 did not use this geometric feature, and (3) reorientation on geometric features generally improved with age.

2.3.2. Landmark condition

The “geometric” search patterns in the yellow-wall room (*landmark condition*) were analyzed with a 5 (age group) × 2 (order: no-landmark condition first versus second) × 2 (corner: correct versus rotational equivalent) mixed ANOVA with mean search frequencies as the dependent variable. The analysis revealed main effects of age group [$F(4,53) = 6.65$, MSE = 0.03, $p < .01$], corner [$F(1,53) = 31.74$, MSE = 0.07, $p < .01$], and significant interactions between age group and corner [$F(4,53) = 6.49$, MSE = 0.07, $p < .01$, all other effects $F \leq 2.03$, $p \geq .10$].

The analysis of the simple effects of the age group by corner interaction revealed that age groups only marginally differed in the frequency with which they chose the rotational equivalent corner [$F(4,53) = 2.26$, MSE = 0.03, $p = .08$], but significantly differed in the frequency with which they chose the correct corner [$F(4,53) = 8.53$, MSE = 0.07, $p < .01$]. Additionally, there were no differences between the correct and the rotational equivalent corner for 2- and 3-year-olds [$F \leq 1.07$, $p \geq .31$]. Four-year-olds chose the correct corner more often than the rotational equivalent corner with marginal significance [$F(1,58) = 3.59$, MSE = 0.08, $p = .06$]. Five- and 6-year-olds searched the correct corner significantly more often than the rotational equivalent corner [$F \geq 14.36$, MSE = 0.08, $p < .01$].[4]

The “nongeometric” search patterns in the yellow-wall room (*landmark condition*) were analyzed with a 5 (age group) × 2 (order: landmark condition first versus second) × 2 (corner: correct versus adjacent landmark-congruent) mixed ANOVA with mean search frequencies as the dependent variable. The analysis revealed main effects of age group [$F(4,53) = 4.98$, MSE = 0.02, $p < .01$], corner [$F(1,53) = 27.92$, MSE = 0.09, $p < .01$], and a significant age group by corner interaction [$F(4,53) = 6.86$, MSE = 0.09, $p < .01$, all other effects $F \leq 1.70$, $p \geq .16$].

Further analysis of the interaction revealed that 4-, 5- and 6-year-olds chose the correct corner significantly more often than the adjacent landmark-congruent corner [$F \geq 6.47$, MSE = 0.09, $p < .01$], whereas there was no difference between search rates at the two corners for the 2- and 3-year-olds [$F < 1$]. Additionally, age groups differed significantly in the frequency with which they chose the correct [$F(4,53) = 8.53$, MSE = 0.07, $p < .01$] and the adjacent landmark-congruent corner [$F(4,53) = 3.04$, MSE = 0.04, $p = .02$].

In order to analyze differences in error frequencies in each of the age groups, mean search frequencies at the rotational equivalent corner were compared to mean search frequencies at the adjacent landmark-congruent corner for each age group separately with paired-samples *t*-tests. There were no significant differences in any of the age groups [$t \leq 1.47$, $p \geq .17$].

Taken together, the analyses for the landmark condition showed that (1) 2- and 3-year-olds searched randomly, (2) 4- to 6-year-olds successfully incorporated geometric and landmark information as revealed by their higher search rates at the correct corner in comparison to the rotational equivalent and the adjacent-landmark congruent corner, and (3) neither landmark nor geometric information dominated search behavior in any of the age groups (no difference in error types). Hence, 5- and 6-year-olds behaved as expected. In contrast, 2- to 4-year-olds behaved largely unexpected in that they failed to show a dominant use of geometric information.

2.4. Discussion

In Experiment 2, we studied children’s reorientation behavior in a locomotor rhombic space. Children ages 4 to 6 used the geometry of the environment in order to find the hidden object: In the all-blue room, they searched at geometrically correct corners more often than at geometrically incorrect locations. Children younger than 4 years of age, however, could not use the overall shape of the apparatus as revealed by their random search behavior. This result contrasts with studies using small rectangular locomotor spaces in which 2-year-olds apparently reoriented on the basis of geometric information (e.g., Hermer & Spelke, 1996). One procedural difference between the studies concerned the hiding location. While Hermer and Spelke hid the object in the same location throughout the experiment,

[4] Additionally, we directly compared the “geometric” search patterns for the landmark and the no-landmark condition with a 5 (age group) × 2 (order: no-landmark condition first vs. second) × 2 (corner: correct vs. rotational equivalent) × 2 (apparatus: landmark vs. no-landmark) mixed ANOVA. The most important result was a three-way interaction between age group, corner and apparatus [$F(4,53) = 2.88$, MSE = 0.06, $p < .05$]. Further analyses of the interaction confirmed the results of the separate analyses.

we changed the hiding location from trial to trial. This might have caused perseveration errors, depressing performance in our 2-year-olds. A recent study on reorientation in an isosceles triangle (Huttenlocher & Vasilyeva, 2003) found that changing the hiding location diminished geometrically correct performances in 2-year-olds, but performance was still above chance. Moreover, they showed that the children represented the different corners in terms of the relative lengths of adjacent walls in combination with sense information rather than in terms of differences in angular information. This suggests that the lack of geometrical coding in our rhombic space might have stemmed from the difficulty of processing/encoding angular information. If this were the case 2- and 3-year-olds should have similar difficulties in using angular information in paradigms other than reorientation.

In the landmark condition, 2- and 3-year-olds continued to search randomly. In contrast, all older children concentrated their searches at the correct corner, showing that they were able to use the landmark. Older children were more likely to conjointly use geometric and nongeometric information,[5] since the frequency of errors did not significantly differ between the adjacent landmark-congruent and the opposite geometry-congruent corner. Neither geometric nor nongeometric information dominated behavior.

Experiment 2 offers no support for the notion that reorientation behavior in young children depends on an encapsulated geometric module incapable of interacting with landmark information. As soon as children were capable of using angular information (4 years of age), they were able to conjoin it with nongeometric information. One striking difference between the Hermer–Spelke work and the present study regards room shape. Hermer and Spelke used rectangular environments, while we used a rhombic room.

Another difference concerns room size. While Hermer and Spelke used small chambers (4 ft × 6 ft), we used a bigger space (7 ft × 7 ft). That the scale of the environment matters was experimentally shown by Learmonth et al. (2001, Learmonth, Nadel, & Newcombe, 2002) who failed to replicate Hermer and Spelke's results in larger rectangular spaces. Specifically, Learmonth et al. (2002) used a within-subject design and replicated the dominant use of geometric features by 3- to 5-year-olds in a 4 ft × 6 ft room. However, the same children flexibly reoriented using nongeometric and geometric features in an 8 ft × 12 ft room. Hermer and Spelke's findings might be limited to small spaces.

3. General discussion

Previous studies reported that young children reorient themselves by using the geometry of an environment while ignoring information provided by salient landmarks. The present study asked whether this finding could be detected in rhombic spaces. The geometric features that can be used to specify locations within a rhombic space are the differences in angles between adjacent corners, with opposite corners sharing the same angular information, and hence being rotationally ambiguous. Target locations can be defined unambiguously only by taking additional landmarks into account.

[5] It should be noted that it is not exactly clear what information participants rely on when they search successfully. In the Hermer–Spelke as well as in our study it remains unclear whether participants indeed incorporate geometric and nongeometric information, or whether they rely on a combination of nongeometric (colored wall vs. non-colored wall) and sense (left vs. right) information.

The first experiment, using a tabletop apparatus, found that in the absence of landmarks 4- to 6-year-old children used angular information to find a hidden object after the egocentric object location was changed by rotating the apparatus. When a salient landmark was added, 4-year-olds neglected geometric information and relied on the nongeometric landmark information. Since the nongeometric information itself was also ambiguous in defining the hiding location, 4-year-olds evenly split their searches between the two landmark-congruent corners. Five- and 6-year-olds were able to combine geometric and landmark information.

The second experiment used a locomotor rhombic space to see whether a navigable space would yield similar results. In contrast to Experiment 1, we did not find dominant use of nongeometric information in any of the age groups. Additionally, and in contrast to Hermer and Spelke (1994, 1996, Hermer-Vazquez et al., 1999, 2001), we found no evidence for dominant use of geometric information. Until the age of 4, children searched randomly, i.e., they used neither geometric nor nongeometric information. At 4 years of age, children did use geometric information, but their behavior reflected the use of nongeometric information as well. This result seems inconsistent with the assumption that reorientation behavior of young children depends upon an encapsulated geometric module. It is also inconsistent with the assumption that landmark information can only be incorporated through the use of spatial language, because at age 4, few children are able to meaningfully apply the terms "left" and "right" (as the spatial production test of Experiment 1 showed, see also Hermer-Vazquez et al., 2001). We observed somewhat different effects in the tabletop (manipulatory) apparatus than in the locomotor space. Manipulatory spaces differ from locomotor spaces in many ways. For instance, manipulatory but not locomotor spaces provide a birds-eye view of the space, and self-reorientation is required only in locomotor spaces. In addition to these factors, the size and navigability of a space seem to play an important role in determining which information young children use to reorient themselves. These factors have the most impact on 4-year-olds' behavior, probably because processing capacities are generally limited at that age. In manipulatory space, 4-year-olds rely solely on nongeometric information (Experiment 1 of the present study; Gouteux, Vauclair, et al., 2001). In small locomotor spaces, 4-year-olds rely solely on geometric information (Hermer-Vazquez et al., 2001). In larger locomotor spaces, 4-year-olds flexibly use both geometric and nongeometric information (Experiment 2 of the present study; Learmonth et al., 2001, 2002). The size of the rhombic space used in Experiment 2 was comparable to the size of the rectangular space used by Learmonth et al. (2001, 2002), so our results could have differed from the Hermer-Spelke findings because of the size of the room, the shape of the room, or both.

We are inclined to the view that the size of the room is the feature that matters, since the large room yielded the same results whatever the shape of the room. We have no definitive explanation for why room size matters. One possibility is that distal and proximal cues play different roles in organizing behavior in space (see Nadel & Hupbach, in press, for further discussion of this possibility). Distal cues are incorporated into representations of the spatial environment, where they contribute to navigation; similarly it is the distal cues that control the firing fields of hippocampal place cells (Cressant, Muller, & Poucet, 1997), and thalamic "head direction" cells (Zugaro, Berthoz, & Wiener, 2001), whose collective activity likely underlies these spatial representations. Small rooms, at the limit, provide only proximal cues, and it is possible that in small spaces “landmarks”, as proximal cues, are indeed not combined with spatial features. This would account for Hermer and Spelke’s results. Large spaces, however, create the possibility of distal landmarks, and their integration with spatial information in the service of navigation.

The bigger picture concerns what these data have to say about the notion of “modularity”, as used by Hermer and Spelke (1994, 1996). We believe our results, in combination with other findings (e.g., Learmonth et al., 2001, 2002) render unlikely the broad claim that a pure geometrical “reorientation” module controls behavior in such a way that nongeometrical information is necessarily excluded. We do not wish, however, to argue against the notion of modules, especially spatial modules. There is little doubt in our view that the hippocampal system of the mammalian brain, and its homologues in other species, constitutes a kind of spatial module. But, in our view it is a module that combines spatial and landmark information whenever such is available.

Taken together, recent studies including the present one provide converging evidence that reorientation abilities of young children are more flexible than initially thought. More research will be needed to sort out the conditions under which landmarks or geometry are used, how these conditions shift with age, and what accounts for the differences between manipulatory and locomotor space, and between locomotor spaces of different sizes.

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