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Are all geometric cues created equal? Children's use of distance and length for reorientation

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A R T I C L E I N F O

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A B S T R A C T

To navigate the world, human adults rely on various types of geometric cues. Yet there is debate over which cues young children use to guide reorientation. Some researchers have argued that particular geometric cues, such as distance, are privileged with respect to navigation, at least early in human ontogeny. On this view, children rely exclusively on distance to regain their orientation. Other geometric cues, such as length, are used for object recognition or two-dimensional form analysis, not reorientation. Here we show that children are capable of using multiple Euclidean cues to reorient, but their ability to use these cues can be masked by global shape information. We argue that children are flexible in their use of geometric cues for reorientation, using both distance and length cues. The role of global shape in facilitating or impeding reorientation is discussed.

1. Introduction

For all mobile organisms, survival is dependent on the ability to navigate the surrounding environment successfully. Because organisms can become disoriented, even in relatively familiar environments, successful navigation may rest on recovering one's orientation. Researchers who study navigation in human and nonhuman animals have long debated the mechanisms that underlie spatial reorientation. At stake in this debate are questions about the extent to which the cognitive mechanisms are shared across species and which environmental cues support reorientation (Cheng, 2008; Cheng & Newcombe, 2005; Gallistel, 1990; Spelke, Lee, & Izard, 2010; Twyman & Newcombe, 2010; Vasilyeva & Lourenco, 2012). The current study was designed to shed light on the latter question by testing what types of geometric properties human children rely on to guide reorientation.

In a seminal study, Cheng (1986) found that rats relied on the geometry of a rectangular chamber to localize a target after a period of brief disorientation. In this study, rats (who were tested individually) were first shown that food was buried in one of the corners of a rectangular chamber. Rats were then removed from the chamber and subsequently returned to a novel position within it. Rats' behaviors revealed that they relied exclusively on the chamber's geometry to search for the food following disorientation (see also, Margules & Gallistel, 1988). When non-geometric features such as distinctive odors or visual patterns at each of the corners were available, they ignored these features, using only the chamber's geometry during their search for the food. This research led to the claim that spatial reorientation in rats was supported by a cognitive module that processes the geometry of surface layouts exclusively, and it is a claim that has since been extended to other animal species and even human children (Hermer & Spelke, 1994; for reviews, see: Cheng, 2008; Cheng & Newcombe, 2005; Twyman & Newcombe, 2010).

Other research, however, has found that human children can, and do, utilize non-geometric features to reorient, providing

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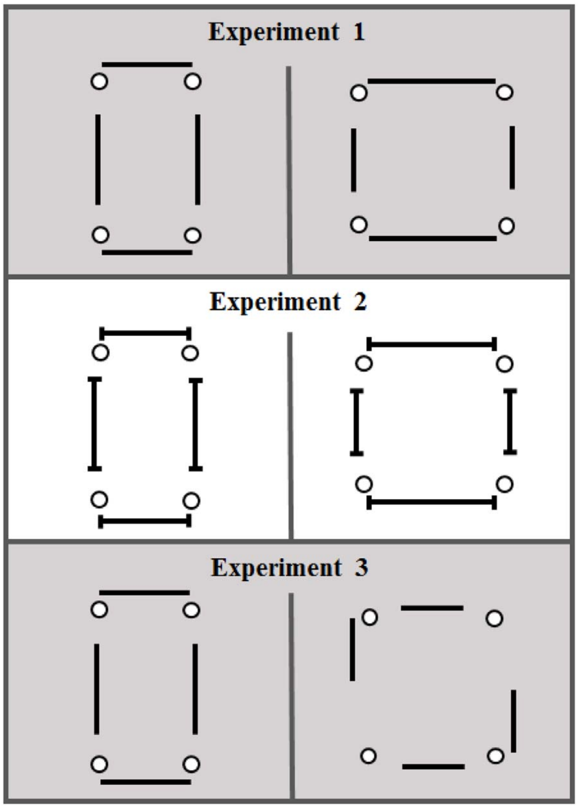

Fig. 1. An illustration of the fragmented spaces used in each condition of the three experiments in the current study (Experiment 1 was a replication of Lee, Sovrano et al. (2012). In Experiments 1 and 2, the distance condition (left panel) was comprised of equal-length walls at different distances whereas the length condition (right panel) was comprised of walls at equal distances but of different lengths. In both experiments, the relevant distances in the distance condition were between the parallel walls, crossing through the centroid of the space. In Experiment 3, a rectangular distance condition (left panel), the same as that in previous experiments, was compared to a square distance condition (right panel), in which the relevant distances were between the edges of the walls and the imputed shape was a square. Circles represent the containers placed at each of the potential hiding locations. The lengths of the walls and the distances between them are to scale. However, the containers and appendages have been enlarged to make them more visible in the figure.

evidence against a reorientation system than relies exclusively on geometry. For instance, although wall color (e.g., a blue-colored wall in a rectangular room) is not used in small spaces (e.g., 4 by 6 feet), it is used reliably in larger spaces (e.g., 8 by 12 feet; Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, Sheridan, & Jones, 2008; Twyman, Friedman, & Spetch, 2007). There are also conditions in which cues unrelated to the spatial layout, such as dot size (i.e., small versus large dots on separate walls of a square space) and luminance (i.e., lighter versus darker gray walls in a square space), are utilized successfully by young children in disorientation tasks (Huttenlocher & Lourenco, 2007; Lourenco, Addy, & Huttenlocher, 2009; Nardini, Atkinson, & Burgess, 2008). More recently, it was even found that wall colors in a kite-shaped space facilitated children's use of the space's geometry following removal of the non-geometric features (Lourenco & Cabrera, 2015).

Although accumulating evidence suggests sensitivity to non-geometric features by human children, an open question is how geometry is represented in the mind and brain given its use across a variety of contexts (Twyman & Newcombe, 2010). In particular, recent research has focused on what properties of geometry children encode and rely upon to guide reorientation. A recent proposal is that reorientation is limited to the processing of a subset of geometric properties (e.g., Spelke et al., 2010). According to Spelke et al. (2010), certain properties of Euclidean geometry, such as distance, are used for reorientation, whereas others, such as length and angle, are used for object recognition and two-dimensional (2D) form analysis. In support of this proposal, Lee, Sovrano, and Spelke (2012) tested children within fragmented spaces of freestanding walls. The fragmented spaces in this research were designed to isolate specific geometric properties such as distance and length (see Fig. 1). In one condition, children were disoriented in a fragmented space composed of equal-length walls positioned at different distances in the shape of a rectangle. In another condition, the fragmented space consisted of pairs of different-length walls positioned at equal distances in the shape of a square. Lee, Sovrano et al. (2012) reported that although children were able to reorient successfully in the former case, as indicated by their searches to the geometrically appropriate locations, they were unable to do so in the latter case. This finding was taken as evidence for preferential processing of distance information in the system guiding reorientation, and it has since been extended to other animal species (i.e., zebra fish; Lee, Vallortigara, Flore, Spelke, & Sovrano, 2013). It has even been claimed that the preference for distance is so prevalent that children may rely on illusory distance information (i.e., illusory depth created by dots of varying sizes on walls in a square space) to reorient (Lee, Winkler-Rhoades, & Spelke, 2012; Spelke et al., 2010).

On the one hand, a preference for distance by children and other species would clearly be adaptive, as it could result in highly efficient processing for the purpose of spatial reorientation. On the other hand, there are clear disadvantages to a lack of flexibility, which raises questions about the claim that the reorientation system (and perhaps navigation more generally) is specialized for processing distance but not other geometric properties. The putative dissociation between distance and length that accompanies the claim of geometric specialization for reorientation is surprising given that distance and length both apply to extended surfaces that, more generally, are implicated in navigation. According to Lee, Sovrano et al. (2012) extended surfaces are more reliable than sources of information such as movable objects and non-geometric features because of their perceived stability (see also Gallistel, 1990). But the place fields of neurons within the hippocampus are not only sensitive to changes in distance, they are also sensitive to the lengths of surfaces (O'Keefe & Burgess, 1996). It is thus unexpected that distance, but not length, would guide reorientation, given that both may be conceptualized in relation to extended surfaces. Moreover, a close examination of the fragmented spaces used by Lee, Sovrano et al. (2012) also reveals a potential confound that could account for the advantage of distance over length. In both the distance and length conditions, global shape could be imputed from the fragmented spaces. The Gestalt principles of closure and continuity would predict that fragmented spaces should be perceived as completed shapes (Koffka, 1935) and evidence from visual attention paradigms suggests that even infants engage in perceptual completion (e.g., Johnson, 2004). The perceptual completion effect with fragmented spaces could override the discrete cues such as the relative lengths of the walls, raising the possibility that children's performance was affected by imputed global shape rather than the discrete geometric properties. In the condition in which distance was presumably isolated, the imputed shape was a rectangle, which may incorporate properties of both distance and length. In the condition in which length was presumably isolated, the imputed shape was a square. Unlike a rectangle, a square shape provides no navigationally-relevant information; that is, the possible locations (at the imputed corners) are indistinguishable from one another on the basis of shape. The difference in imputed global shape across the two conditions calls for further investigation of the claim that reorientation in children relies exclusively on particular geometric properties.

1.1. Current study

In this study, we sought to address two questions. First, we asked whether spatial reorientation in human children is guided exclusively by distance, as recently claimed. Although the debate over modularity in this literature originally focused on children's difficulty using non-geometric cues (e.g., Hermer & Spelke, 1994), the debate has now shifted to whether reorientation by young children is specific to only a subset of geometric properties (e.g., Spelke et al., 2010). Research with fragmented spaces suggests that the distances between extended surfaces, but not the lengths of those surfaces, guide reorientation in children (e.g., Lee, Sovrano et al., 2012). Second, we asked about the potential role of global shape information in reorientation. Above, we suggested that confounded global shape could account for children's performance within fragmented spaces. Indeed, other research in fully enclosed spaces is consistent with children encoding the complete shapes of spaces, not the isolated components (Cheng and Newcombe, 2005; Gallistel, 1989; Huttenlocher & Vasilyeva, 2003; Lew, Gibbons, Murphy, & Gavin Bremner, 2010; Margules & Gallistel, 1988).

In a first experiment, we tested children in two fragmented spaces, similar to those used by Lee, Sovrano et al. (2012). One space was composed of equal-length walls, which, if completed, formed a rectangle. The other space was composed of equidistant walls of varying lengths, which, if completed, formed a square (see Fig. 1). To anticipate the results of this experiment, we replicated the findings of Lee, Sovrano et al. (2012) in that children reoriented successfully in the distance condition (i.e., restricting their searches to the two geometrically correct locations) but not in the length condition. That is, when global shape could be imputed, children succeeded in the distance condition (with imputed rectangular shape) but failed in the length condition (with imputed square shape).

In two subsequent experiments, we manipulated the global shape information accompanying the fragmented spaces to test the impact of global shape on children's use of distance and length following disorientation. In our second experiment, we added appendages to the ends of the walls of the fragmented spaces to disrupt the perceptual completion effect (see Fig. 1). Of particular interest was whether children would now be able to use length information to reorient, given that the global shape should no longer mask the lengths of the walls. In our third experiment, we returned to conditions without appendages to test the effect of imputed global shape on distance information when the walls were positioned in the shape of a square (see Fig. 1). To test for the use of distance information in a square space, the walls were adjusted such that the relevant distances were between the ends of the walls. Although this type of distance information contrasts with that in a rectangular space, it allowed use to test whether length and distance are treated comparably for the purpose of reorientation. If they are, then the availability of a square shape should impede children's use of distance as it does for length (Lee, Sovrano et al. (2012) Experiment 1 here).

In all experiments, we tested preschool-aged children with a mean age of approximately 46 months. Although the original work of Lee, Sovrano et al. (2012) tested younger children (approximately 30 months of age), our own pilot work suggested that younger children had difficulty with the design of our experiments, which included multiple blocks of trials (see Method sections below). Importantly, however, subsequent research by Dillon, Huang, and Spelke (2013) suggests that the specialization for distance within the reorientation system continues through the preschool age, lending support to the age range selected for the current study.

2. Experiment one

2.1. Method

2.1.1. Participants

Twenty-eight preschool-aged children (M = 42.00 months, *range* = 30.96–53.88 months; 14 girls) participated in this experiment. Two additional children were tested but failed to complete the task; their data were thus excluded from statistical analyses. Informed consent was provided by a parent or legal guardian on behalf of each child. All experimental procedures were approved by the local Institutional Review Board (IRB).

2.1.2. Design and procedure

Each child was tasked with localizing a hidden object following a brief period of disorientation, similar to previous studies (e.g., Hermer & Spelke, 1994; Learmonth, Newcombe, & Huttenlocher, 2001; Lourenco, Huttenlocher, & Vasilyeva, 2005). Children were tested individually by an experimenter in a fragmented space made up of four freestanding walls (see Fig. 1). Four identical containers were placed in between the walls at what would be considered the corners of a fully connected space. This space was positioned centrally within a larger circular enclosure (diameter = 3.35 m, height = 2.60 m) to prevent the use of outside landmarks. Children were told that they would be playing a “hiding and finding game” and selected four toys to hide. During each trial, the child hid one of the toys inside a predetermined container, which was the same on each trial (location counterbalanced across children). Children were then disoriented by closing their eyes and spinning around as the experimenter counted to ten (approximately 5 rotations). The experimenter closely monitored children throughout this procedure to ensure that their eyes were covered and that they continuously spun around. Following disorientation, children were positioned by the experimenter in front of a different wall on each trial (randomly determined). Children were encouraged to search for the toy until they found it, but only the first search was scored, as in previous research (e.g., Hermer & Spelke, 1994).

All children completed two blocks of four trials each (8 trials total). One block corresponded to the distance condition and the other to the length condition. Both conditions consisted of four walls (each 47 cm high). In the distance condition, the walls were equal in length (102 cm), but placed at different distances apart (see Fig. 1). Here, the relevant distances were those between the parallel walls, which crossed perpendicularly at the centroid of the space. Children in this condition were successful if they relied on distance (e.g., far wall) and direction (e.g., left) information to localize the target, yielding two possible geometrically identical choices (e.g., locations that are to the *left* of the *farther* wall). In the length condition, the distances were held constant but the walls differed in length (69 cm vs. 137 cm; see Fig. 1). Here, a successful reorientation strategy involved relying on length (e.g., long wall) and direction (e.g., left), again yielding two geometrically identical choices (e.g., locations that are to the *left* of the *longer* wall). As in the study by Lee, Sovrano et al. (2012), the walls in the distance condition were positioned such that the overall shape formed a rectangle if the space was completely connected (area = 3.53 m^2) whereas the walls in the length condition were positioned such that they formed a square (area = 4.09 m^2). Order of conditions was counterbalanced across children such that an equal number of children experienced each condition first.

2.2. Results

In a first analysis, we examined children’ search accuracy using a 2 × 2 mixed factor analysis of variance (ANOVA); condition (distance, length) served as a within-subjects factor and order (distance condition first, length condition first) as a between-subjects factor.[1] Accuracy in each condition was scored as proportion of searches to the target location (i.e., where the toy was hidden) or the geometric equivalent. This analysis yielded significant main effects of condition, $F(1, 26) = 8.29$, $p < 0.01$, $\eta_p^2 = 0.24$ (see Fig. 2), and order, $F(1, 26) = 16.31$, $p < 0.001$, $\eta_p^2 = 0.39$, as well as a significant interaction between these two factors, $F(1, 26) = 4.30$, $p < 0.05$, $\eta_p^2 = 0.14$ (see Fig. 3, Appendix A). Post hoc comparisons revealed that performance was better in the distance condition compared to the length condition in the first, but not second, block of trials (first block: $t[26] = 5.46$, $p < 0.001$; second block: $t[26] = 0.64$, $p > 0.50$).

In subsequent analyses, we examined whether performance in each condition differed from chance. Overall performance in the distance condition was significantly better than chance ($M = 0.69$, $SE = 0.06$), $t(27) = 3.38$, $p < 0.005$, $d = 1.30$, though this was driven exclusively by children who experienced the distance condition first ($p < 0.001$; see Fig. 3). Children who experienced the distance condition second did not perform significantly above chance ($p > 0.80$; see Fig. 3). Children’s performance in the length condition did not differ significantly from chance in either block ($ps > 0.25$; see Fig. 3, Appendix A).

To confirm that children were successfully disoriented in the task, we compared search at the target location with the geometrically equivalent location. If disorientation is successful, then children should search at these locations equally often because they are indistinguishable from one another on the basis of geometric information. In both conditions, children’s performance was equivalent at these locations (distance condition: $t[27] = 1.53$, $p > 0.10$; length condition: $t[27] = 0.58$, $p > 0.50$; see Fig. 2, Appendix A), confirming that children were disoriented.

A separate ANOVA, with gender and hiding location as between-subjects factors, was conducted on the distance condition to determine whether children’s success in this condition varied by gender or hiding location. There was no main effect of gender ($p > 0.20$) or hiding location ($p > 0.10$) and no significant interaction between these factors ($p > 0.40$; see Appendix A). Age was also unrelated to performance in the distance condition ($p > 0.70$).

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[1] Some studies (e.g., Ferrara & Landau, 2015; Lakusta, Dessalegn, & Landau, 2010) have used non-parametric analyses to analyze similar data in order to avoid possible violations of statistical assumptions. Following these studies, we include non-parametric tests in an Appendix. The results of the non-parametric tests converge with those reported in the main text.

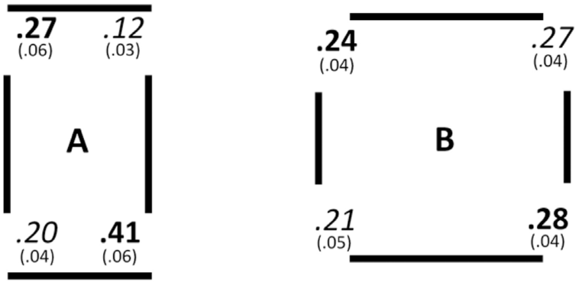

Fig. 2. Conditions and results of Experiment 1. Mean proportion correct is depicted for each location by condition (SE in parentheses). For both the distance condition (A) and the length condition (B), the target location is represented by the top-left value and the geometric equivalent by the bottom-right value. The lengths of the walls and the distances between them are to scale.

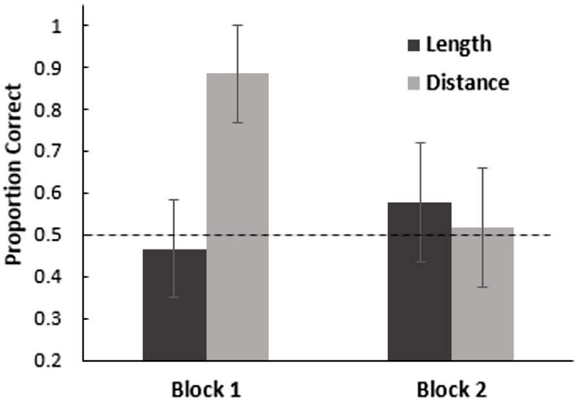

Fig. 3. Mean accuracy in Distance and Length conditions as a function of block. Children performed better in the Distance than Length condition, but only in the first block of trials. Moreover, only children who experienced the Distance condition first performed above chance (chance indicated by the dotted line). Performance in all other condition/block combinations did not differ significantly from chance. Error bars represent 95% confidence intervals.

2.3. Discussion

The findings from this experiment replicate and extend those of Lee, Sovrano et al. (2012). As in their work, we found that children were able to reorient in the distance, but not the length, condition, though the effect in the distance condition was only apparent early in the experimental session. Although both distance and length are properties of Euclidean geometry, and although both apply to extended surfaces, a prevalent claim is that they are *not* psychologically equivalent within the domain of navigation (Dillon et al., 2013; Lee, Sovrano et al., 2012; Lee & Spelke, 2010; Lee et al., 2013; Spelke et al., 2010). The claim is that early in human development (and among nonhuman animals) reorientation is guided by a subset of geometric properties, namely distance (and direction). Length is not used for reorientation because it is a property of Euclidean geometry that is accessed by a separate system specialized for object recognition and 2D form analysis. According to this view, only following experience with symbolic representations such as spatial language and maps do humans come to rely flexibly on different geometric properties for navigation (Dillon et al., 2013; Spelke et al., 2010).

The challenge for claiming specificity of distance for the purpose of reorientation is that in the current study, and in that of Lee, Sovrano et al. (2012), the geometric information of interest (distance vs. length) was confounded with the imputed global shape (that is, the illusory shape formed by the contour of the walls, if connected). Crucially, in the length condition, the walls were positioned such that the shape of the fragmented space formed a square, which does not allow for distinguishing the target location from the others. If children represented global shape, then their performance in this condition might suffer, not because of their exclusive use of distance when reorienting, but because the imputed square shape did not provide any relevant geometric information for distinguishing locations. The specific problem in this condition is that the imputed global shape (square) conflicts with the available discrete geometric properties (walls of different length). By contrast, in the distance condition, the walls were positioned so as to form a rectangle, which does not conflict with the relevant distance information.

We thus conducted a second experiment in which the primary aim was to test whether children could use relative wall length to reorient when they were unlikely to impute global shape from the fragmented space. We created new fragmented spaces that were identical to those of Experiment 1 except that perpendicular appendages were added to the ends of the walls (see Fig. 1). We reasoned that these appendages would disrupt perceptual completion as predicted by Gestalt principles and thus increase the salience of the relevant length information. If children are capable of using length for the purpose of reorientation, then they should reorient successfully in this condition. However, if there is truly an advantage for distance over length when children reorient in a spatial environment, then they should continue to fail to distinguish among the locations, as in the previous experiment. A distance condition (also with appendages) was included for comparison because, as in the length condition, the appendages should disrupt the global shape information (rectangle). However, as noted above, because the global shape here does not conflict with the relevant distance information, we did not predict a change in children's performance compared to the previous experiment. Thus, if one expects that children are capable of using both distance *and* length for reorientation, then it follows that children should reorient successfully in both conditions.

3. Experiment two

3.1. Method

3.1.1. Participants

Twenty-eight preschool-aged children (M = 48.33 months, *range* = 42.72–56.88 months; 14 girls) participated in this experiment. Three additional children were tested but failed to complete the task, and their data were excluded from subsequent analyses. Informed consent for each child was provided by his or her parent or legal guardian. All experimental procedures were approved by the local IRB.

3.1.2. Design and procedure

All elements of the design were identical to Experiment 1 except that perpendicular appendages (23 cm in length) were attached to the ends of each wall (see Fig. 1). As in the previous experiment, all children completed two blocks of four trials (8 trials total), with one block corresponding to the distance condition and the other to the length condition (counterbalanced order across children). Correct searches were those to the target location or its geometric equivalent.

3.2. Results

As in Experiment 1, we first analyzed children's performance (i.e., accuracy at the geometrically correct locations) using a mixed factor 2 (condition: distance, length; within-subjects) × 2 (order: distance condition first, length condition first; between-subjects) ANOVA. This analysis revealed no significant effects (condition: $F[1,26] = 2.66$, $p > 0.10$; order: $F[1,26] = 0.20$, $p > 0.60$; condition × order: $F[1,26] = 0.02$, $p > 0.90$; see Appendix A). Thus, unlike the previous experiment, children did not perform better in the distance condition in either block (see Fig. 4).

An additional analysis comparing children's performance to chance revealed that accuracy was above chance in both distance and length conditions. Children searched at the geometrically correct locations in the distance condition significantly above chance ($M = 0.74$, $SE = 0.05$), $t(27) = 4.67, p < 0.001$, $d = 1.80$ (see Fig. 4A, Appendix A). Crucially, children also showed above chance performance in the length condition ($M = 0.63$, $SE = 0.04$), $t(27) = 2.79$, $p < 0.05$, $d = 1.07$ (see Fig. 4B, Appendix A). Thus, children in this experiment were able to use either distance or length information to distinguish locations following disorientation.

As in the previous experiment, and following the general standard in the literature, we examined whether the disorientation procedure was successful by comparing children's searches at the target location to the geometrically equivalent location. In the length condition, children searched equally at these locations, $t(27) = 1.14, p > 0.25$, confirming disorientation (see Appendix A). Children in the distance condition, however, showed a preference for the target location compared with its geometric equivalent, $t(27) = 2.25, p < 0.05$. Because the disorientation procedure in both conditions was identical, it is unlikely that children were not disoriented in the distance condition. Nevertheless, to ensure that the effects above could not be explained by the extent of disorientation across the two conditions, we removed the two children from the distance condition who searched at the target location on all trials. When these children were excluded from the analysis, there was no longer a statistical difference between the target and geometrically equivalent location ($p > 0.10$; see Appendix A). Moreover, and crucially, removing these children did not affect the pattern of results. In particular, the remaining children in the distance condition performed above chance ($M = 0.71$,

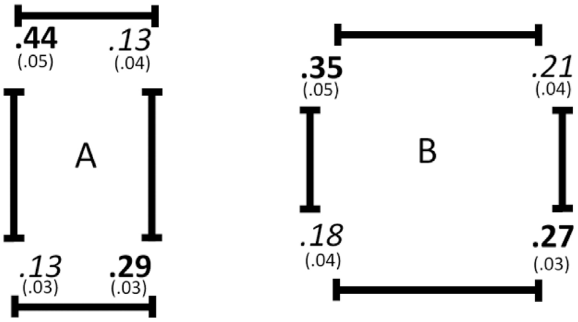

Fig. 4. Conditions and results of Experiment 2. In both conditions, appendages were attached to the ends of the walls. Mean proportion correct is depicted for each location by condition (SE in parentheses). The results for Distance (A) and Length (B) conditions are shown such that the target location is represented by the top-left corner and the geometric equivalent by the bottom-right. The lengths of the walls and the distances between them are to scale. However, the appendages have been enlarged to make them more visible in the figure.

$SE = 0.04$), $t(25) = 4.12$, $p < 0.001$, $d = 1.65$ (see Appendix A), and performance in the distance condition was not significantly better than in the length condition ($p > 0.15$).

Separate ANOVAs, with gender and hiding location as between-subjects factors, were conducted to determine whether children's success in each condition could be explained by these variables. There were no main effects of gender ($ps > 0.05$) or hiding location ($ps > 0.40$) and no interaction between these two factors ($ps > 0.70$; see Appendix A) in either condition. Age was not significantly correlated with performance in either condition ($ps > 0.30$).

3.3. Discussion

The results of our second experiment demonstrate that children were capable of using length information to guide reorientation and, crucially, that they performed comparably across length and distance conditions. Children are thus not restricted to distance information to reorient in a spatial environment, as has been claimed (e.g., Lee, Sovrano et al., 2012; Spelke et al., 2010). They are capable of relying on wall length. Children's ability to use length in the current experiment provides empirical support for our hypothesis that the results of previous work (Lee, Sovrano et al., 2012) may have been a consequence of imputed global shape. In the absence of appendages, the square shape of the spatial layout may have masked the use of the discrete geometric cues. However, when the Gestalt information of the global shape was attenuated, children were capable of using wall length for reorientation. The appendages in the distance condition may have also weakened the saliency of the rectangular shape, but, crucially, the relevant discrete geometric property (distance) was preserved. Accordingly, and consistent with our hypothesis, we conclude that children can use both distance *and* length for reorientation when these cues are not masked by global shape. Altogether, these findings demonstrate greater flexibility in children's use of Euclidean geometric properties for the purpose of reorientation, providing evidence against a modular perspective which posits that, at this stage in development, reorientation relies exclusively on a subset of geometric properties (e.g., Spelke et al., 2010).

Nevertheless, a concern with the current work is that the children were slightly older than those in the work of Lee, Sovrano et al. (2012). Accordingly, one might argue that the children here only succeeded at using length because they reached an age when length becomes accessible to the reorientation system. We would argue against this because children in the first experiment were unable to use length despite being somewhat older than those in the study of Lee, Sovrano et al. (2012). If age were the critical variable, then children in our previous experiment should have also been able to use the length of the walls to reorient. Moreover, we included age in our analyses and found no relationship between performance and age in this or the previous experiment.

Thus, we would suggest that children's inability to use length in a fragmented space is affected by the availability of global shape. That children were capable of using length when global shape was less likely to be imputed supports this proposal. However, greater support for this proposal would come from showing that global shape similarly impedes children's use of distance for reorientation. An open question is whether length and distance are treated comparably within a reorientation system. Researchers who claim that reorientation relies on a subset of geometric cues would argue that distance and length are not psychologically equivalent because of their use by different systems, namely reorientation and object/form systems (e.g., Lee & Spelke, 2010). It is thus critical to test whether distance and length are similarly impacted by global shape. If so, it would provide support for their psychological equivalence and would further argue against specificity for reorientation by children. In the next experiment, we tested whether children's ability to reorient by way of distance information was hampered when the fragmented space formed a square layout. To this end, we provided children with distance in a fragmented, square-shaped enclosure, which, in this space, involved the distances between the ends of the walls (see Fig. 5). If length and distance cues are comparable in their potential to guide reorientation, then children should fail to reorient using distance information in a space in which the imputed global shape is a square—just as they failed with length information within the square environment (Experiment 1). A distance condition in the shape of a rectangle, as in Experiments 1 and 2, was included for a within-subjects comparison.

4. Experiment three

4.1. Methods

4.1.1. Participants

Twenty-eight preschool-aged children ($M = 48.96$ months, $range = 42.10–57.8$ months; 16 girls) participated in this experiment. Consent was provided for each child by the parent or legal guardian, and all experimental procedures were approved by the local IRB.

4.1.2. Design and procedure

In this experiment, we tested children's ability to use distance in two conditions. Both conditions were identical in that there were four walls of equal length with pairs of locations distinguishable by the relative distances (see Fig. 1). The critical difference was that in one of the conditions, distance information was presented in a fragmented rectangle (area = 3.90 m^2), whereas in the other condition it was presented within a fragmented square (area = 4.09 m^2), resembling the shape of the length conditions in the previous experiments. The square enclosure was made up of four equal-length walls (76 cm), two of which were placed 130 cm off-center (see Fig. 5). Consequently, unlike previous experiments, the relevant distance information was not between parallel walls and did not extend through the centroid of the space. Instead, the relevant distances were between the edges of the walls: two sets of walls were close to one another (see top-left and bottom-right of Fig. 5) and two sets of walls were farther from one another (see bottom-left and top-right of Fig. 5). The distances between the far sets of walls were approximately twice the distance between the near sets of

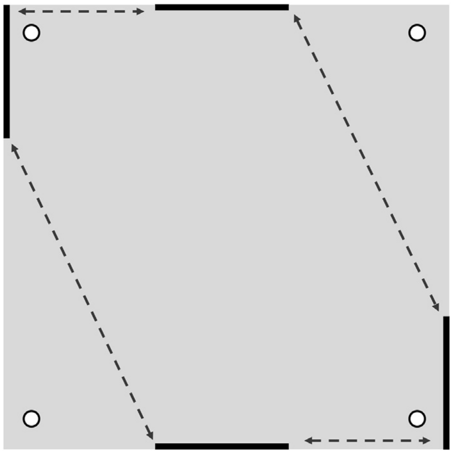

Fig. 5. Illustration of the Square condition in Experiment 3. In this condition, the relevant distance information is not between the walls and the centroid of the space. Instead, the relevant distances were between the edges of the walls, as indicated by the dashed lines. The longer distances (bottom-left and top-right) were approximately twice the extent of the shorter distances (top-left and bottom-right).

walls (mirroring the distance ratio in previous experiments). Children completed two blocks of trials (8 trials total), one of which was completed within the rectangular enclosure (i.e., rectangle condition) and the other of which was completed within the square enclosure (i.e., square condition). Order of conditions was counterbalanced across children. All other procedural aspects were identical to the previous experiments.

4.2. Results

A mixed factor 2 (condition: rectangle, square; within-subjects) × 2 (order: rectangle condition first, square condition first; between-subjects) ANOVA yielded a significant main effect of condition, $F(1, 26) = 7.86$, $p < 0.01$, $\eta_p^2 = 0.23$, but no effect of order, $F(1, 26) = 0.42$, $p > 0.50$, nor an interaction between these two factors, $F(1, 26) = 0.10$, $p > 0.70$ (see Appendix A). Children performed better in the rectangle condition than the square condition regardless of the order of conditions. Moreover, comparisons to chance revealed above-chance performance only in the rectangle condition ($M = 0.67$, $SE = 0.04$), $t(27) = 3.80$, $p < 0.001$, $d = 1.46$ (see Fig. 6A, Appendix A). Children performed at chance in the square condition ($M = 0.51$, $SE = 0.03$), $t(27) = 0.27$, $p > 0.70$ (see Fig. 6B, Appendix A), demonstrating an inability to use distance information in this condition.

As in the previous experiments, we ensured that children were successfully disoriented by comparing search at the target and geometrically equivalent locations. In both conditions, children's performance was equivalent at these locations (rectangle condition: $t[27] = 0.93$, $p > 0.30$; square condition: $t[27] = 0.15$, $p > 0.80$; see Fig. 6, Appendix A), confirming disorientation.

To determine whether children's success in the rectangle condition varied by gender or hiding location, we ran a separate ANOVA with gender and hiding location as between-subjects factors. This analysis revealed no effects of gender ($p > 0.90$) or hiding location ($p > 0.05$) and no interaction between these factors ($p > 0.30$; see Appendix A). Age was also not significantly correlated with performance in the rectangle condition ($p > 0.30$).

4.3. Discussion

The results from this experiment demonstrate that children were unable to use distance when this information was available

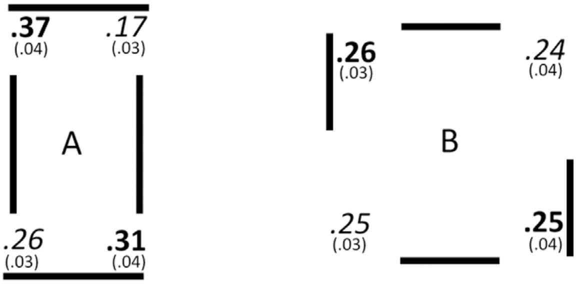

Fig. 6. Conditions and results of Experiment 3. The Rectangle condition (A) matches the distance condition in Experiment 1. The Square condition (B) was composed of four equal-length walls, two of which were placed off-center to create relevant distance information. In both conditions, the target corner is represented by the top-left location and its geometric equivalent is represented by the bottom-right. The lengths of the walls and the distances between them are to scale.

within an imputed square shape. Thus, like length, the use of distance was hampered by the presence of irrelevant global shape information. (Children were again capable of using distance within an imputed rectangular space.) Together with the previous experiment, the findings from Experiment 3 demonstrate that children's use of distance and length is similarly modulated by imputed global shape, suggesting a psychological equivalence of distance and length in guiding reorientation.

We would acknowledge, however, that there is an alternative possibility for why children might have had difficulty using distance within an imputed square space. The relative distances within this space may have been more difficult to extract and/or maintain in memory than when relative distances were available within a rectangular space. In a rectangular layout, the relevant distances exist along perpendicular axes. By contrast, in the square layout implemented here, the relevant distances consisted of distances between the ends of the walls, which were not directly orthogonal to one another, and which may have made the task more challenging. Indeed, there is evidence, at least in the visual modality, that comparisons across perpendicular dimensions may be privileged (e.g., Huttenlocher, Hedges, Corrigan, & Crawford, 2004). Although we cannot refute this possibility directly, we would note that whether due to imputed global shape or a limitation in comparing non-orthogonal distances, our results demonstrate that, like length, children's use of distance for reorientation is context dependent. That is, distance information, like length, may not always be used by young children for the purpose of reorientation, though both types of geometric properties are within their repertoire. Our findings suggest greater similarity in the navigational significance of distance and length than currently acknowledged.

5. General discussion

How do young children recover from spatial disorientation? A prevalent proposal is that this ability recruits a subset of Euclidean geometric properties (e.g., Dillon et al., 2013; Lee, Sovrano et al., 2012; Spelke et al., 2010). According to this view, distance is used for reorientation, whereas other properties, such as the length of walls (tested here) or the angular size of corners (see Lee, Sovrano et al., 2012), are not. This view holds that different geometric properties are recruited for distinct functions (i.e., navigation versus object and 2D form perception), at least when exposure to symbolic representations, namely spatial language and maps, is minimal (Dillon et al., 2013; Spelke et al., 2010).

In the current study, we addressed the strong claim of geometric specialization by comparing children's ability to reorient by way of distance or length cues. In particular, we tested whether the putative distance advantage in guiding reorientation could be explained by the availability of global shape information provided by the arrangement of the walls. We replicated the effects of Lee, Sovrano et al. (2012) by showing that when imputed global shape was confounded with distance and length, children succeeded in a distance, but not length, condition (Exp. 1). However, in subsequent experiments, we demonstrated that children were able to use length at comparable levels to distance when a manipulation of the spatial layout reduced the likelihood of imputing global shape (Exp. 2) and we demonstrated that children's use of distance was hampered when irrelevant global shape could be imputed (Exp. 3).

Taken together, the findings from the current study suggest three conclusions. The first is that children are not restricted to distance when navigating the spatial environment. The claim that distance is used for reorientation whereas other geometric properties are not is based largely on children's inability to use length when this information is available as fragmented surfaces positioned in the shape of a square (Lee, Sovrano et al., 2012). Yet when imputed global shape was attenuated, we found that children used length to guide reorientation reliably and at comparable levels to distance. Although others have suggested that distance, but not length, guides reorientation, our findings demonstrate that this is not the case when taking imputed global shape into account.

The second conclusion is that length and distance share functional significance. Even in the face of neural specificity for these geometric properties (and indeed, there is evidence suggesting that place cells in rats respond differentially to changes in distance and length; for review, see Burgess, 2008), our data show that children are capable of using different types of geometric properties for the purpose of reorientation. The data from the current study extend those from previous work where it has been found that children use non-geometric cues such as different colored walls (e.g., Learmonth et al., 2008; Nardini et al., 2008) to reorient by demonstrating that they also have access to a variety of Euclidean properties that characterize the spatial environment. Moreover, they challenge the claim that navigation dissociates from a system of object recognition and form perception on the basis of geometric properties such as distance and length, since children have access to both types of information under comparable conditions when navigating.

A final conclusion that arises from our findings relates to the prevalence of global shape among spatial layouts. Children clearly use length and distance to reorient, but the imputed global shape, even when irrelevant, affects the processing of these cues (cf. Huttenlocher & Vasilyeva, 2003). Why might this be the case? It is possible that global shape is simply more salient than discrete geometric properties such as distance and length and, thus, differentially captures children's attention. Research with non-human animals supports this notion: when rats were given experience in two compartments separated by a boundary, grid cells firing in medial entorhinal cortex formed a representation of the larger shape of the space, as opposed to representing each compartment separately (Carpenter, Manson, Jeffery, Burgess, & Barry, 2015). Thus, both behavioral and neural findings demonstrate that global shape overrides discrete properties and suggest a privileged status for this type of information in navigation. Indeed, the stability associated with extended surfaces and boundaries within the environment may contribute to a privileged status for representations of shape, even if only imputed (Gallistel, 1990; Lee, Sovrano et al., 2012).

Beyond the specific conclusions above, our findings also have implications for the relevance of 'shape' and its underlying computations. As we have operationalized it here, global shape refers to the imputed shape derived from the exterior contours of the space. Many researchers concerned with navigation have made attempts to define shape (e.g., Cheng & Gallistel, 1984; Lee & Spelke, 2010), with some noting the relevance and computations applied to the constituent parts (Gallistel, 1990; Lee, Sovrano et al., 2012). For instance, in an early formulation, Gallistel (1990) described shape as "defined by the distances between and along surfaces (or lines) and by the angles they form, that is, by the uniquely metric relations" (p. 173). By contrast, there are structural description models of shape that capture the overall structure of a space but do not precisely represent each component part (for review, see Cheng, 2005). Such models include the principal axes or medial axis, both of which capture the internal structure of the space. Especially in rectangular spaces, which are commonplace in reorientation experiments, one could argue that these models emphasize particular geometric properties, namely the distance or distances that cross the centroid of space. Thus, it would follow that distance information might in fact play a greater role than properties such as length or angle in supporting shape-based navigation, given that these other properties are either not captured (as in a principal axis model) or are less prominent (as in a medial axis model). Yet our work shows that young children are capable of using different geometric properties when reorienting, suggesting flexibility in their access to these properties. As such, our findings may help to constrain theories about shape computation, particularly in the context of spatial reorientation.

6. Summary

In summary, we have argued that spatial reorientation by children is supported by a system that has access to multiple geometric properties. By demonstrating that children use the lengths of walls to reorient, we provide evidence of flexibility in their use of geometry. We also found that children's use of length and distance cues was affected by the global shape of the environmental layout. We thus argue against the claim that reorientation by human children is exclusively supported by distance. Instead, children represent different geometric parameters, including discrete properties such as distance and length as well as more general properties such as global shape, when navigating within a spatial environment.

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Appendix A

Experiment 1

Analysis	Test	Statistic	p
Effect of condition	Wilcoxon Signed Ranks Test	$Z = 2.21$	0.03
Effect of order (Distance)	Mann Whitney U Test	$Z = 3.41$	< 0.01
Effect of order (Length)	Mann Whitney U Test	$Z = 1.20$	0.23
Disorientation check (Distance)	Wilcoxon Signed Ranks Test	$Z = 1.46$	0.15
Disorientation check (Length)	Wilcoxon Signed Ranks Test	$Z = 0.56$	0.58
Comparison to chance (Distance)	Wilcoxon Signed Ranks Test	$Z = 2.89$	< 0.01
Comparison to chance (Length)	Wilcoxon Signed Ranks Test	$Z = 0.42$	0.67
Effect of hiding corner (Distance)	Kruskal-Wallis Test	$X^2 = 7.27$	0.06
Effect of gender (Distance)	Mann Whitney U Test	$Z = 0.50$	0.64

Experiment 2

Analysis	Test	*Statistic*	p
Effect of condition	Wilcoxon Signed Ranks Test	$Z = 1.52$	0.13
Effect of order (Distance)	Mann Whitney U Test	$Z = 0.43$	0.66
Effect of order (Length)	Mann Whitney U Test	$Z = 0.34$	0.73
Disorientation check (Distance)*	Wilcoxon Signed Ranks Test	$Z = 1.64$	0.10
Disorientation check (Length)	Wilcoxon Signed Ranks Test	$Z = 0.97$	0.33
Comparison to chance (Distance)*	Wilcoxon Signed Ranks Test	$Z = 3.25$	< 0.01
Comparison to chance (Length)	Wilcoxon Signed Ranks Test	$Z = 2.50$	0.01
Effect of hiding corner (Distance)	Kruskal-Wallis Test	$X^2 = 2.82$	0.42
Effect of hiding corner (Length)	Kruskal-Wallis Test	$X^2 = 2.00$	0.57
Effect of gender (Distance)	Mann Whitney U Test	$Z = 0.17$	0.89
Effect of gender (Length)**	Mann Whitney U Test	$Z = 2.29$	0.02

Experiment 3

Analysis	Test	*Statistic*	*p*
Effect of condition	Wilcoxon Signed Ranks Test	$Z = 2.64$	< 0.01
Effect of order (Rectangle)	Mann Whitney U Test	$Z = 0.32$	0.77
Effect of order (Square)	Mann Whitney U Test	$Z = 0.25$	0.84
Disorientation check (Rectangle)	Wilcoxon Signed Ranks Test	$Z = 0.81$	0.42
Disorientation check (Square)	Wilcoxon Signed Ranks Test	$Z = 0.38$	0.71
Comparison to chance (Rectangle)	Wilcoxon Signed Ranks Test	$Z = 3.00$	< 0.01
Comparison to chance (Square)	Wilcoxon Signed Ranks Test	$Z = 0.28$	0.78
Effect of hiding corner (Rectangle)	Kruskal-Wallis Test	$X^2 = 7.23$	0.07
Effect of gender (Rectangle)	Mann Whitney U Test	$Z = 0.05$	0.96

*The analyses here do not include two children, as explained in the main text.

**The effect of gender reflected better performance by girls than boys. Because this effect was not predicted, and because of the small sample size, we do not speculate about the possible reasons for the gender difference in this one case.

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