Core knowledge and the emergence of symbols: The case of maps

Abstract

Map reading is unique to humans but present in people of diverse cultures, at ages as young as 4 years. Here we explore the nature and sources of this ability, asking both what geometric information young children use in maps and what non-symbolic systems are associated with their map-reading performance. Four-year-old children were given two tests of map-based navigation (placing an object within a small 3D surface layout at a position indicated on a 2D map), one focused on distance relations and the other on angle relations. Children also were given two non-symbolic tasks, testing their use of geometry for navigation (a reorientation task) and for visual form analysis (a deviant-detection task). Although children successfully performed both map tasks, their performance on the two map tasks was uncorrelated, providing evidence for distinct abilities to represent distance and angle on 2D maps of 3D surface layouts. In contrast, performance on each map task was associated with performance on one of the two non-symbolic tasks: map-based navigation by distance correlated with sensitivity to the shape of the environment in the reorientation task, whereas map-based navigation by angle correlated with sensitivity to the shapes of 2D forms and patterns in the deviant detection task. These findings suggest links between one uniquely human, emerging symbolic ability, geometric map use, and two core systems of geometry.

Humans are unique in developing and mastering productive symbol systems to benefit their survival. One symbol system uses Euclidean plane geometry to represent the 3D navigable world in the form of a map. Map use develops early in childhood: By 3 to 4 years, children can use distance scaling and spatial configurations on simple maps to find objects in a large space, without any guidance or feedback (Huttenlocher, Newcombe, & Vasilyeva, 1999; Landau, 1986; Shusterman, Lee, & Spelke, 2008). This ability is found even in congenitally blind children without any map reading experience (Landau, 1986; Landau, Spelke, & Gleitman, 1984). Nevertheless, older children use spatial representations of large environments more reliably and flexibly (Deloache, 2004; Hardwick, McIntyre, & Pick, 1976; Kosslyn, Pick, & Fariello, 1974; Newcombe & Huttenlocher, 2003; Uttal, 1996), providing evidence that map-reading skill increases over development.

What accounts for young children's limited abilities to read maps? One difference between the tasks on which young children succeed and those on which they fail concerns the complexity of the layouts through which children must navigate. Young children tend to fail tasks in which maps present complex arrangements of barriers, furniture and other objects (e.g., Kosslyn, et al., 1974), whereas they tend to succeed on tasks in which maps present simple triangular or rectangular arrays, devoid of objects and depicted only by lines or simple forms. A second difference concerns the size of the represented environment: many map tasks that young children fail require that they navigate to places that are visible on the map but not in the immediate environment, because the map depicts multiple rooms or large outdoor layouts and the target location lies beyond occluding walls or other surfaces (Piaget, Inhelder, & Szeminska, 1960; Pick, 1972). A third difference concerns the nature of the information represented on the map. Although maps primarily capture geometric relations within the layout, most maps, including those first solved by older children, also represent landmarks by their names or visual features. Research suggests that both adults and children use these landmarks at an early age, when they serve as direct cues to the location of an object (DeLoache, 1987; Shusterman, et al., 2008). In contrast, young children fail to navigate by landmark representations on a map when the landmark serves as an indirect cue to a hidden object and therefore must be combined with geometric information (Rutland, Custance, & Campbell, 1993; Shusterman, et al., 2008). Indeed, both children and adults show higher sensitivity to geometric information when maps are devoid of such landmarks than when they contain them (Dehaene, Izard, Pica, & Spelke, 2006; Shusterman, et al., 2008): representations of the geometry of the layout and of individual landmark objects may be mutually competitive (Lourenco, Addy, Huttenlocher & Fabian, 2011).

The fourth difference bearing on young children's map performance concerns the child's relation to the environment. The tasks that young children fail place the child within the environment that is depicted on the map. Such maps differ from the environments they represent not only in scale (the map is smaller than the layout), orientation (in map tasks as in ordinary navigation, the orientation at which a map is encountered typically is not the same as that of the environment that it represents) and dimensionality (the map collapses the 3D layout into two dimensions), but also in perspective (the child stands outside the map, but is inside, and surrounded by, the layout that it depicts). In contrast, the tasks on which young children have succeeded in past studies present the first three challenges but not the fourth: they place the child outside the depicted environment. When one views a map of an environment that one stands outside, it is possible to navigate by forming a global image of the array on the map and searching for the best matching global image of the surrounding environment. When one stands inside the depicted array, in contrast, no global image, even a panoramic one, resembles the image on the map.

In an effort to understand better young children's map-based navigation, we presented children with the task of navigating by a map that depicts a simple environment lacking distinctive landmarks that preserves only the last property of the more difficult map tasks: it depicts the shape of the environment that surrounds the child. To minimize demands on attention and working memory, both the map and the environment consist of a single, simple geometrical form, the environment has no occluding walls, and the map depicts no distinctive landmark objects. Thus, we test whether young children can navigate by a purely geometric representation of the surrounding 3D environment when the representation differs from the environment in scale, orientation, dimensionality, and perspective.

We also begin to investigate the information that children use to guide their map reading. Geometric maps typically are small, moveable, 2D depictions of large, stable 3D surface layouts: small lines represent the contours of extended surfaces, and points represent specific locations. In such maps, locations can be indicated by the *distance* relations between points or lines, and by the *angular* relations between lines that meet at corners. Four-year-old children spontaneously use distance relationships in simple maps to find specific locations in 3D object arrays with little or no training and feedback (Huttenlocher, et al., 1999; Shusterman, et al., 2008). Children's sensitivity to angle in maps is less clear, however, because angle and distance are confounded in most maps. In the triangular environments tested in many map tasks, for example, corners of distinctive angles are flanked by sides of distinctive distances (Shusterman, et al., 2008). Angle and distance can be deconfounded by presenting partial maps (for example, a piece of a map that presents a full corner but incomplete sides of a triangle), and research using this method reveals sensitivity to angle at 4.5 years of age (Izard, O'Donnell, & Spelke, in press). Four-year-old children have difficulty navigating by fragmented maps, however, and their ability to use angle in complete maps remains unknown.

Angle information might be especially useful for young children's map-based navigation, because angular sizes are invariant over changes in scale. At 6 years of age, children use both distance relations and angle relations on a partial map of an environment viewed from outside, in locating positions within an array of surfaces that they also view from outside (Spelke, Gilmore, & McCarthy, 2011). At 4 years of age, however, the contributions of distance and angle to children's map reading have not been fully disentangled, and they have not been tested with maps depicting the full environment that surrounds the child. Here we present 4-year-old children with two such map tasks, one encouraging the use of angle information and the other encouraging the use of distance information. We assess children's use of each source of information by analyzing their error patterns on each task.

Finally, we begin to probe the non-symbolic systems of spatial representation that may contribute to children's map reading. Our investigation is based on evidence that much younger children have two such systems of spatial representation, each of which is shared by other animals (see Spelke & Lee, 2012, for review). First, children have a system for representing the distances and directions of extended surfaces in the surrounding layout. This system first was described by Cheng (1986), based on studies of the behavior of disoriented rats searching for food, who reoriented by the shape of their rectangular environment. Many animals, including children, reorient by layout geometry (see Cheng & Newcombe, 2005; Spelke, Lee, & Izard, 2010, for reviews), as do fish and chicks with minimal navigation experience (Brown, Spetch, & Hurd, 2007; Chiandetti & Vallortigara, 2010; Vallortigara, Sovrano, & Chiandetti, 2009). Although reorientation has been modeled by image-matching processes (e.g., Sheynikhovich, Chavarriaga, Strosslin, Arleo, & Gerstner, 2009; Sturzl, Cheung, Cheng, & Zeil, 2008; Wystrach, Cheng, Sosa, & Beugnon, 2011), image-matching cannot readily account either for the findings of neurophysiological experiments on rats (e.g., Lever, Wills, Cacucci, Burgess, & O'Keefe, 2002) or for the performance of children who respond to subtle depth information (Lee & Spelke, 2011; Lee & Spelke, 2010; Lee, Winkler-Rhoades & Spelke, 2012). These findings and others (see Spelke & Lee, 2012) suggest that a phylogenetically ancient system for navigating by layout geometry emerges early in human development.

Second, children have a system for recognizing objects based on their shapes. Evidence for geometry-based object recognition and form analysis also comes from multiple sources (see Izard, et al., 2011; Landau & Lakusta, 2009, for reviews). Sensitivity to 2D shape begins in human infancy (Schwartz & Day, 1979) and underlies object recognition and visual form analysis in children (Izard & Spelke, 2009) as well as adults in diverse cultures (Dehaene, et al., 2006). Abilities to perceive the shapes of objects and forms are found in animals from insects (e.g. Lehrer & Campan, 2005) to birds (e.g., Blough & Blough, 1997) to primates (Tanaka, 2003). Although children's shape representations undergo changes with age and experience (Smith, 2009), these findings suggest that a system for analyzing the shapes of objects also is widespread across animals and early emerging in humans.

Further research provides evidence that human navigation and object recognition depend on distinct neural and cognitive systems, each with its own specializations and limits (Derdikman& Moser, 2010; Doeller, Barry, & Burgess, 2010; Doeller, King, & Burgess, 2008; Kourtzi & Kanwisher, 2001, see also Mishkin & Ungerleider, 1982). For present purposes, the most important distinction between these systems concerns the geometric relationships that each captures. Studies of navigating rats provide evidence for neural representations of the distances and asymmetric directions of extended surfaces, but not the lengths of surfaces or the angular sizes of corners where surfaces meet (e.g., Lever, et al., 2002). Consistent with these findings, disoriented children relocate hidden objects to the left or right of equal-length surfaces that differ in distance, but not equidistant surfaces or corners differing in length or angle (Hupbach & Nadel, 2005; Lee, Sovrano, & Spelke, 2012). Studies of visual form analysis and object recognition reveal nearly the reverse pattern: young children use relative length and angle to distinguish one form from another, but their perception of forms is invariant over changes in scale (i.e., distance) and sense (i.e., the asymmetric directional relation that distinguishes a shape from its mirror image; see Izard, et al., 2011, for review). Many animal species show the same performance pattern (see Spelke & Lee, 2012).

Thus, neither system captures all the basic properties of Euclidean plane geometry. Nevertheless, is possible that the geometric system for representing the distances and directions of large-scale surface layouts could guide children's use of distance in maps, and the system for representing the relative lengths and angles of visual forms could guide their use of both length and angle in maps. We use an individual difference method to begin to test these hypotheses.

We presented 4-year-old children with four spatial tasks. Children were given two map tasks in which they stood inside a triangular environment and placed targets at locations in the environment indicated by their locations on a 2D map depicting a small triangle of the same shape. In one map task, targets were located at the corners of the triangle, which differed in angle. In the other map task, targets were located at the sides of the triangle, which differed in their lengths and distances from the child's location at the triangle's center. Children also were given two non-symbolic tests tapping systems of core geometry: the classic reorientation task within a rectangular enclosure to assess their use of geometric distance for navigation, and a deviant detection task to assess their sensitivity to a variety of geometrical properties of visual forms.

Correlational analyses probed relationships between children's performance on each of these tasks. If children's map use depends in part on the geometric representations guiding navigation, then children's reorientation performance should correlate with map-based navigation by distance (but not angle). If map reading also depends in part on geometric representations guiding form analysis, then children's detection of deviant forms should correlate with sensitivity to both angle and length relationships (but not distance) on the map. Finally, if children respond to distance and angle information on the map in an integrated fashion, then performance on the corner map task and the side map task should be correlated with one another. In contrast, if the side map task elicits different representations and processes than the corner map task, then success at one of these tasks may not be associated with the success at the other task.

Methods

Participants

Forty-nine children (24 boys, mean age 4;5, range 3;7 – 5;6) were tested in one (N = 27) or two (N = 22) sessions. All children contributed data to the two map tasks and reorientation task, and 37 also contributed data to the form analysis task (see below). Four additional children were eliminated for failing to complete the map task.

Testing overview

Children participated in two map tasks, three reorientation sessions, and one visual form analysis task. Because disorientation procedures can induce a state of dizziness if they are not followed by breaks, the three reorientation sessions were separated in time as far as possible by beginning with the first reorientation session, then giving the visual form analysis task between the first and second reorientation sessions, then giving the two map tasks after the second reorientation session, and ending with the third reorientation session. Two children lost interest after two reorientation sessions; only the data from their first two sessions were analyzed. For 34 children, the form analysis task used verbal labels that were poorly understood by children; data from this task were not analyzed. The last 15 children in the sample, together with 22 children (out of 34) who returned to the lab for a second visit, received the deviant detection form analysis task. No other tests were given.

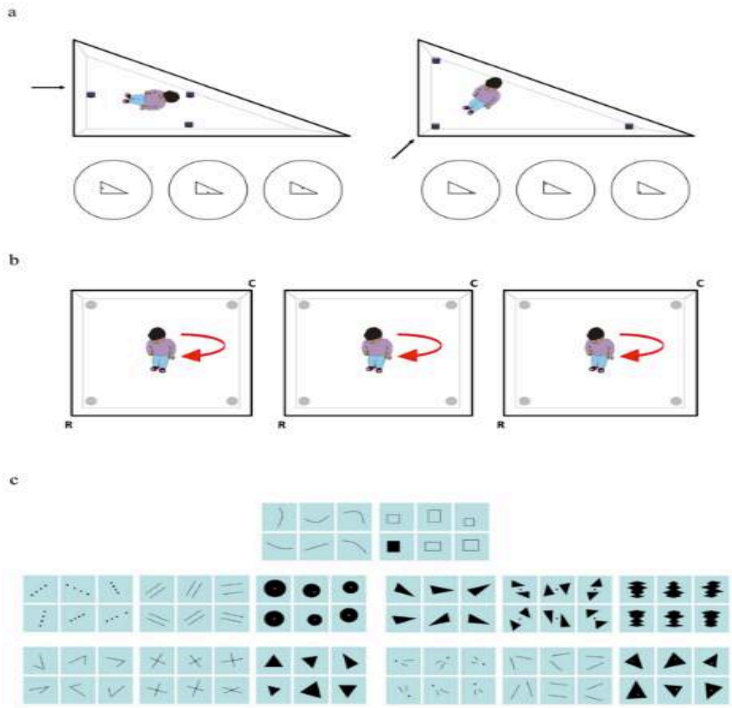
Testing for the map tasks and the reorientation task took place within a sound-proofed circular chamber made of white curved panels (one serving as a spring-operated door), a grey floor, and symmetrically mounted lights and camera-equipped ceiling. Testing for the form analysis task took place at a desk in a room adjacent to this chamber.

Displays

For the map task, one 51cm high triangular enclosure, made of white foam board and placed at the center of the circular chamber, served as the navigable environment. The enclosure was a right triangle (hypotenuse, 152.4 cm, legs, 132 cm and 76.2 cm, angles of 30°, 60° and 90°). Three purple caps (diameter 11.5 cm), placed either at the centers of the inside walls or at corners, served as the locations on which children could place a small stuffed animal (Figure 1*a*). The maps, printed on laminated white paper, consisted of 6 circular images with a triangular form in the middle and a single purple dot either at a corner (corners test) or at the center of a side (side test: Figure 1*a*). Each map depicted the triangular enclosure and one of the three caps within the surrounding room from an accurate overhead view at a scale of 1/25.

Reorientation was tested in three 61 cm high enclosures made of 1.3 cm thick white foam board, with subtly rectangular shapes: 99 x 91.5cm, 103 x 91.5 cm, and 107 x 91.5cm (Figure 1*b*). During testing, each enclosure was centered in the round room. Four paper plates (diameter, 10cm) placed on the floor at the four corners, served to hide the targets (colorful stickers). Visual form analysis was tested with materials adapted from Dehaene et al. (2006) and Izard et al. (2011). On each trial, six images were presented on 28 x 21cm laminated paper. Five of the images shared one geometric property (length relations, angle relations, asymmetric relations, or parallelism/alignment) and the sixth did not (Figure 1*c*); the intruding image appeared at different positions across trials. Each geometric property was tested in three different arrays (total, 12 arrays). Two practice arrays exhibited other properties of figures (see Figure 1*c*).

Figure 1



Design and Procedure

For the map task, the triangular enclosure was positioned in the room, and the child stepped inside while the experimenter remained outside. For each trial, the experimenter showed a map to children, handed them an animal and encouraged them to place it on its seat, marked by a purple dot on the map. Children were tested on the three corner or side locations in immediate succession; the order of these tests was counterbalanced between participants. The map was presented at a constant orientation, positioned behind the middle of a different side (side test) or corner (corner test) on each of the three trials (order counterbalanced across participants)

(Figure 1*a*). The orientation of the map relative to the array therefore varied across trials. Children's object placements were coded from an overhead video record of the test session.

The reorientation test was based on that of Lee & Spelke (2008) and took the form of a hiding and finding game. Children were tested in the three enclosures in one of three orders: easiest-moderate-hardest (18 participants), hardest-easiest-moderate (15) or moderate-hardest-easiest (16). To reduce proactive interference, the target location was constant for each child and counterbalanced across participants. The child faced a different wall at the start of each search trial; facing direction was counterbalanced both within and across participants. To discourage use of inadvertent cues outside the enclosures, the orientations of the enclosures varied across sessions. Each child was lifted inside a rectangular enclosure by the experimenter, who then hid a sticker under one plate. After the child indicated, by pointing, where the sticker was hidden, the experimenter helped the child put on a blindfold and then turned around with him/her in place several times to induce disorientation. The experimenter stopped the child at a particular facing direction, removed the blindfold while standing behind the child, and encouraged him/her to find the sticker. Children's parents observed the experiment from a video monitor outside the testing room. A small number of children refused to enter the room without a parent; they were accompanied by one parent, who walked around the outside of the enclosure while the child turned. The first search was recorded as the child's response.

The visual form analysis task procedure was based on that of Izard et al.

(2011). Children were asked to find the intruding image in each array of six images. To accustom children to this task, the experimenter first showed the practice arrays, asking the child which picture was most different and why; incorrect or irrelevant answers were corrected. For test trials, children pointed to the intruder and received neutral feedback. Trial order was quasi-random with intermixed trials testing different geometric relations. The child's first point to an image served as the response.

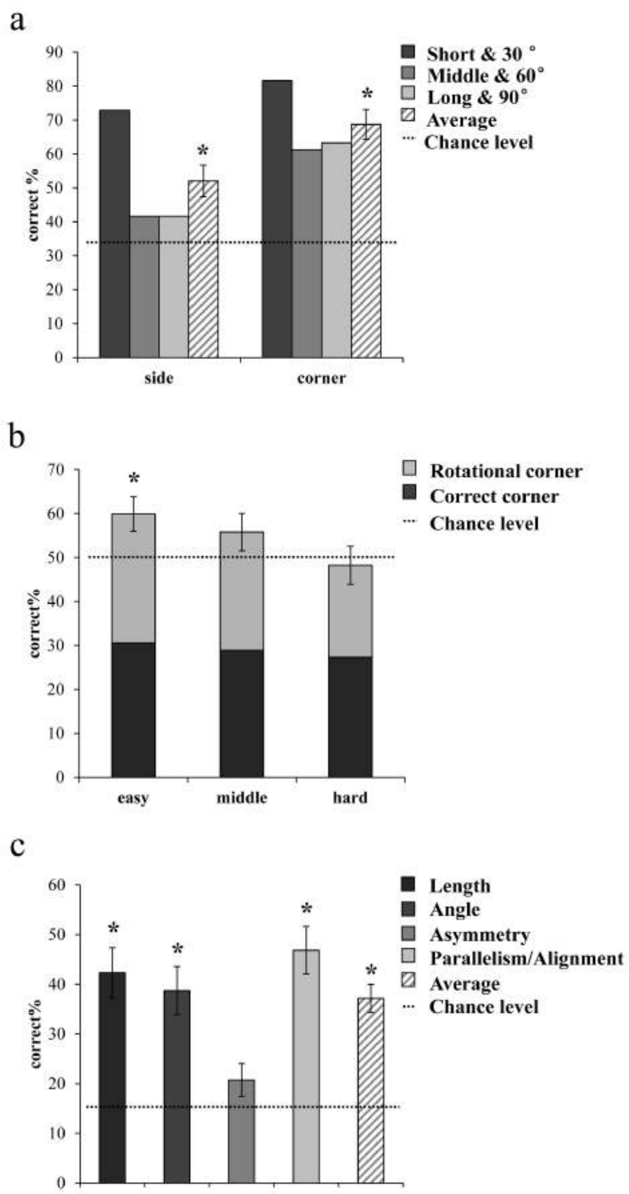
Results

Children performed significantly above chance (33%) on both versions of the map test, with targets at the sides (51%, $t(48) = 3.870$, $p < .001$, *Cohen's d* = 0.553) and corners (68%, $t(48) = 8.056$, $p < .001$, *Cohen's d* = 1.151) of the triangular array. Children performed better with corners than with sides ($t(48) = 3.212$, $p = 0.002$, *Cohen's d* = 0.459; Figure 2*a*). On side trials, children performed best when the target appeared on the shortest side, whose length and distance differed most strongly both from that of the middle side ($\chi^2(1) = 8.522$, $p < 0.01$, *Cohen's d* = 0.918) and that of the longest side ($\chi^2(1) = 7.759$, $p < 0.01$, *Cohen's d* = 0.866). Because the shortest side was flanked by the corners whose angles were least distinctive, this finding suggests that children focused on side lengths or distances. On angle trials, children performed better when the target appeared at the smallest corner than at the middle corner ($\chi^2(1) = 5.786$, $p < 0.05$, *Cohen's d* = 0.732) but they did not perform significantly better at the smallest corner than at the largest one ($\chi^2(1) = 3.522$, $p > 0.05$). Nevertheless, children's performance was highest when the target appeared at the corner with the most distinctive angle, flanked by sides of the least distinctive lengths (see Figure 2*a*), consistent with a map strategy focused on angles.

On the reorientation test, children searched equally at the correct and geometrically equivalent opposite corners (all ts(48) < 1.2, $p > 0.23$; for 99 x 91.5cm session, $df = 46$), and at the incorrect near and far corners (all ts(48) < 1.3, $p > 0.21$; for 99 x 91.5cm session, $df = 46$) for all three sessions, indicating they were disoriented. The proportion of searches at the geometrically appropriate corners (C and R) reliably exceeded chance (50%) only in the 91.5:107 chamber (60%, $t(48) = 2.539$, $p = 0.014$, *Cohen's d* = 0.371). Children's performance increased linearly as the aspect ratio of the enclosure departed further from 1 (Figure 2*b*); a planned test on this linear trend was significant ($F(1, 142) = 3.979$, $p = 0.048$).

On the visual form analysis test, children detected the geometric intruder at levels well above chance (17%), both overall (37%, $t(36) = 7.349$, $p < .001$, *Cohen's d* = 1.208), and on the subtests of distance (42%, $t(36) = 5.194$, $p < .001$, *Cohen's d* = 0.854), angle (39%, $t(36) = 4.649$, $p < .001$, *Cohen's d* = 0.764), and parallelism or alignment (47%, $t(36) = 6.369$, $p < .001$, *Cohen's d* = 1.047), but not on the subtest of asymmetry (21%, $t(36) = 1.245$, $p = 0.221$, *Cohen's d* = 0.205) (Figure 2*c*). These findings are consistent with previous findings that children are sensitive to length, angle, and relations of parallelism and alignment on 2D geometric forms, but not to the sense relations that distinguish a form from its mirror image or a symmetrical form from an asymmetrical one (Izard, et al., 2011).

Figure 2



To test for interrelations among these tasks, first we compared performance on the two map tests to one another. If children process distance and angle information in an integrated fashion on the map tasks, then performance on these two tasks should be highly correlated, because every trial presents both distance and angle information, and distance and angle information systematically covary in all triangular arrays. Contrary to this prediction, there was only a weak and non-significant positive relationship between children's performance on the two map tasks ($N = 49$, $r = 0.245$, $p = 0.09$). Although the side and corner map tests may elicit some common capacity for symbolic processing, there was no strong relationship between children's sensitivity to distance/length and to angle on the map.

Next we tested for relationships between children's performance on the two non-symbolic tasks tapping early-developing geometric representations in children and animals. Children who received both the tests of reorientation and geometrical form analysis were included in the analysis (i.e. 37 participants). Their overall performance on the two tests also was uncorrelated ($r = 0.073$, $p = 0.666$): those who showed the highest sensitivity to geometry on the reorientation task were no more likely than other children to show high sensitivity to geometry on the form analysis task.

Finally, we tested for relationships between performance on each of the two map tasks with performance on reorientation and form analysis. Children's performance on the side map test correlated with performance on the test of reorientation ($N = 49$, $r = 0.292$, $p = 0.042$, $R^2 = 0.085$) but showed a weaker, non-significant correlation with performance on test of visual form analysis ($N = 37$, $r = 0.286$, $p = 0.086$). In contrast, performance on the corner map test correlated with performance on the test of form analysis ($N = 37$, $r = 0.400$, $p = 0.014$, $R^2 = 0.160$) and not with performance on the test of reorientation ($N = 49$, $r = -0.037$, $p = 0.800$).

Each of the tests of navigation by geometric maps therefore was related in a distinct way to children's performance on tests assessing core geometry. Map-based navigation by distance correlated with performance on a test of reorientation, which depends in part on sensitivity to distance relations, and map-based navigation by angle correlated with performance on a test of visual form analysis, which depends in part on sensitivity to angular relations.

Discussion

The present experiment adds to understanding of children's map-reading abilities. First, it shows that four-year-old children can match a 2D map with the surrounding 3D layout, not only over transformations of scale, orientation, and dimensionality but over a considerable transformation of perspective. Children make sense of an external map that depicts the environment that surrounds and contains them. In this respect, preschool children already show a hallmark capacity of map-reading in adults: an ability to relate the external viewpoint depicted on the map to their sense of their own position inside the depicted surface layout.

Furthermore, the findings help to clarify the kinds of geometric information that children can use in this map-reading task. They provide evidence that angular relations, as well as distance relations, guide children's map-based navigation. Although children have been shown in many studies to interpret relations of distance or length on maps (e.g., Huttenlocher, et al., 1999; Shusterman, et al., 2008), the present study is one of the first to provide evidence for the use of angle information in preschool children (in accord with the findings of Izard et al., in press) and the first showing use of angle to interpret a map of the environment that surrounds the child. Angle information should be especially useful for map-guided navigation, because angular sizes are invariant over the transformations of scale and orientation that relate small, moveable maps to large, fixed spatial layouts. Consistent with this possibility, we find that sensitivity on angular relations is as good as or better than sensitivity to distance or length relations, in the connected surface arrays presented in this study. When children are presented with a purely geometric map of a connected triangular enclosure, they evidently are highly sensitive to angle.

The present experiment also suggests that the map-reading abilities of 4-year-old children are systematically related to their sensitivity to geometry as it is manifested in two non-symbolic tasks of navigation and form analysis. In this regard, the individual differences method used in this study yielded three noteworthy findings. First, children's use of geometry for reorientation was correlated with their performance on the map test in which a target was hidden at a side of distinctive length and distance. This finding cannot be explained by individual differences in intelligence or motivation, because it is specific to these tasks: reorientation performance failed to correlate with performance on the corner map test, and side map test performance correlated non-significantly with performance on the visual form analysis test. The findings also cannot be explained by superficial similarities between the stimuli or tasks used to assess reorientation and map-based navigation by distance, as the two map tests were far more similar to one another than either was to the test of reorientation.

The positive correlation of reorientation with the side map test strengthens the evidence that children's reorientation depends on an analysis of geometric information for surface distance, contrary to a popular theory that it depends on an analysis of 2D retinal patterns (e.g., Cheng, 2008). Moreover, it is consistent with the hypothesis that children's use of distance information in maps draws on representations and processes that are shared by their use of distance information in non-symbolic navigation tasks (Lee Sovrano & Spelke, 2012; Lee, Winkler-Rhoades & Spelke, 2012). Although reorientation depends on a highly encapsulated process whose inner workings are opaque to intuition in adults (Gallistel, 1990; Hermer & Spelke, 1996), some of its outputs may be available to children for use in an explicit, symbolic task.

The second finding from the individual differences analyses was a correlation between children’s use of geometric information for visual form analysis and their performance on the angle map test. This correlation also may be specific to these two tasks, because geometrical form analysis correlated only non-significantly with performance on the side map test. Because the test of form analysis used diverse displays and a very different task from the map test, the correlation between these tasks cannot be explained by superficial similarities between them. It suggests that some information about the shapes of visual forms can be accessed for use in a symbolic navigation task. It is possible that the same representations of angular relationships underlie children's visual form analysis and their mapping of corner locations in a map to corner locations in a 3D surface layout.

The third notable finding from the individual differences analyses was a negative one: the variability in children's use of geometry for reorientation was uncorrelated with variability in children's use of geometry for form analysis, even though each of these tests showed meaningful correlations with map use. This negative finding complements the evidence for distinct systems of navigation and form analysis from behavioral and neuroimaging research on human adults (e.g., Doeller, et al., 2008; Kourtzi & Kanwisher, 2001), behavioral and neurophysiological studies of monkeys (e.g., Mishkin, Ungerleider, & Macko, 1983), and linguistic analyses of word meanings across languages (Landau & Jackendoff, 1993). To our knowledge, no previous study has directly probed the relationship between these systems in young children by means of an individual difference approach. Our findings suggest that in young children, as in adults, spatial ability does not vary along a single dimension. Children have at least two non-symbolic systems for analyzing the shapes of objects and of navigable layouts (Landau & Lakusta, 2009; Spelke, 2011).

The present findings suggest parallels between the development of spatial and numerical cognition. For adults, the simplest and most intuitive concepts in the domain of number are the positive integers or "natural numbers": the numbers that we use in counting. Despite their intuitiveness, however, research on the development of numerical cognition suggests that the natural numbers are constructed by children from two distinct cognitive systems: a system for distinguishing among small sets exactly and representing the operation of adding one, and a system for representing larger sets with approximate precision and for representing the operation of comparing cardinal values (e.g., Carey, 2009; Feigenson, Dehaene, & Spelke, 2004; Izard, Pica, Spelke, & Dehaene, 2008). Similarly, the simplest and most intuitive concepts in the domain of geometry are the relations of distance and angle that distinguish among points, lines and figures on the Euclidean plane: the geometrical objects that we use to interpret maps. Despite the intuitive force of these concepts, however, the present findings suggest that Euclidean plane geometry is constructed by children from two distinct systems as well. Just as young children fail to connect two numerical relations that jointly define the natural numbers--the successor relation (plus one) and the relation of numerical equivalence--young children fail to connect two geometrical relations that jointly define the objects of Euclidean plane geometry--the relations of distance and angle.

Nevertheless, young children have two distinct systems of geometry, also with distinct signature limits, that they can use to construct Euclidean geometry: a system guiding navigation through surface layouts and a system guiding object recognition and visual form analysis (Landau & Lakusta, 2009; Spelke, et al., 2010). The contrasting signature limits of these two systems--one is sensitive primarily to distance and the other to angle--appear not only on non-symbolic tasks of navigation and form analysis but on the symbolic task of reading a map. Moreover, the precision and robustness of the geometric representations that guide children's navigation is unrelated to that of the geometric representations that guide children's visual form analysis.

A further parallel between the development of geometrical and numerical concepts comes from research probing relationships between children's performance in non-symbolic and symbolic tasks. Previous research reveals an association between the precision of children's non-symbolic numerical representations and their facility at both learning and performing symbolic mathematics (Gilmore, McCarthy, & Spelke, 2010; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011). Although our research includes no measures of mastery of school mathematics, we find two associations between non-symbolic and symbolic geometrical abilities: (a) the precision of children's representations of geometry for reorientation is correlated with their facility at using distance or length relationships on a map, and (b) the proficiency of children's representations of geometry for visual form analysis is correlated with their facility at using angle relationships on a map. In neither case do these findings reveal the causes of these associations. Nevertheless, the findings suggest that common processes of some kind underlie the spatial as well as the numerical abilities that young children exhibit in non-symbolic and symbolic tasks.

It is sometimes suggested that by mastering symbols, children gain the means to combine the outputs of their early-developing systems for representing space, allowing for more flexible spatial performance (Landau & Lakusta, 2009; Spelke, et al., 2010). By using maps, for example, children may begin to view navigable layouts not only as extended surfaces but as visual forms, and they may begin to view manipulable objects not only as visual forms but as arrays of surfaces that can be approached from different distances and directions. In this way, children may discover new relations between Euclidean lengths, angles, distances, and directions, yielding new geometric concepts. If such an integrative process exists, however, the present findings provide no evidence that it has begun to function at four years of age. In the present triangular map task, children's sensitivity to distance barely correlates with their sensitivity to angle, despite the strong interdependence of these geometric variables in any Euclidean triangle. It is possible that distance and angle become integrated later in development (Izard, et al., 2011). Studies using the present methods with older children could serve to investigate this possibility.

The present findings raise further questions for future research. First, do children use relationships of length, distance, or both when they navigate by maps? Although length and distance are correlated in any connected triangle, experiments using fragmented figures could serve to test separately for map-based navigation by length vs. distance. Recent studies of reorientation in fragmented environments reveal that children reorient by distance but not length (Lee, et al., 2012). Similar experimental manipulations could serve to test whether young children can flexibly use length in map tasks, or whether their abilities to find a target location with respect to an extended surface depends only on the surface's distance.

Another question for future research concerns the relative strength of the statistical contribution of each core geometric system to predicting children's performance with symbolic maps. The pattern of simple correlations found in the present experiment suggests that processes involved in reorientation and visual form analysis make independent contributions to children's reading of symbolic maps.

Hierarchical regression analyses cannot test this suggestion, however, for two reasons. First, the relative contributions of the two core systems to children's map performance cannot be compared, because the tests by which we assessed each of the core systems differed in difficulty. Children's performance on the form analysis task exceeded chance on three of the four subtests, whereas performance on the reorientation test rose above chance only for one of three arrays. Second, only 37 children contributed data to all three of these tasks, and this sample size is not sufficient for hierarchical analyses of performance. If future studies presented tasks of comparable difficulty to a larger sample of children, then regression models could serve to calculate the distinctive contribution of each of the measures of core abilities to children's map-reading.

Despite these limitations, the contrasting correlations of reorientation with distance-based map use, and of visual form analysis with angle-based map use, indicate that children have differing performance profiles on the higher-level symbolic tasks of deciphering distance and angle in a geometric map. Because the present experiment is the first to test interrelationships among these abilities in children, to our knowledge, and because the measures reported in this article are the only measures taken on these children, these interrelationships cannot be attributed to the selection biases that have plagued some past research (Simmons, Nelson, & Simonsohn, 2011).

In summary, the present study reveals that both distance and angle guide the map-based navigation of 4-year-old children, over changes in scale, dimensionality, orientation and perspective. The dissociated correlations between children's use of distance vs. angle on maps, and their performance on tests of reorientation and form analysis, suggest that performance on tests tapping core knowledge can predict specific features of young children's symbolic spatial performance. We hope this study sparks a larger project linking understanding of the universal, core systems that humans share with animals, to understanding of the development of culturally variable, historically progressing symbolic systems that constitute some of the highest hard-won achievements of our species.

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Figure Legends

*Figure 1.*The displays used in the experiment. (a) Schematic depiction of the apparatus and maps used in the side condition (left) and corner condition (right) of the map task. For each condition, the upper figure presents an overhead view of the enclosure and one of the three positions of the experimenter presenting the map to children (arrow); the lower figure presents the three maps used for that condition. Each map was presented at the depicted orientation, relative to the child, and therefore at a different test position and orientation relative to the enclosure. (b)The reorientation apparatus, viewed from above, used for the most difficult (left), moderately difficult (center), and easiest (right) reorientation tests. C indicates one target location; C and R indicate the geometrically correct searches for that target location. (c) The displays used for practice (top) and to test sensitivity to each of four different geometrical properties in the test of visual form analysis: distance and length (top left), asymmetry (top right), angle (bottom left), and parallelism/alignment (bottom right).

Figure 2. Children's performance on the tests of map interpretation, reorientation and form analysis. (a) Percent correct target placements for the two map-based navigation tasks. (b) Percent of total search trials that were directed either to the correct corner or to the geometrically equivalent opposite corner on in each of the three arrays used in the reorientation task. Error bars indicate ±1 standard error of the averaged percent

of both corners. (c) Percent correct choices for each geometrical property tested on the visual form analysis task. Asterisks indicate above-chance performance (one-sampled *t* tests，2-tailed).