

The Representation of Geometric Cues in Infancy

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There is evidence that, from an early age, humans are sensitive to spatial information such as simple landmarks and the size of objects. This study concerns the ability to represent a particular kind of spatial information, namely, the *geometry* of an enclosed layout—an ability present in older children, adults, and nonhuman animals (e.g., Cheng, 1986; Hermer & Spelke, 1996). Using a looking-time procedure, 4.5- to 6.5-month-olds were tested on whether they could distinguish among the corners of an isosceles triangle. On each trial, the target corner was marked by a red dot. The stimulus (triangle with dot) appeared from different orientations across trials, ensuring that only cues related to the triangle itself could be used to differentiate the corners. When orientations were highly variable, infants discriminated the unique corner (i.e., the corner with the smaller angle and two equal-length sides) from a nonunique corner; they could not discriminate between the two nonunique corners. With less variable orientations, however, infants did discriminate between the nonunique corners of the isosceles triangle. Implications for how infants represent geometric cues are discussed.

The representation of spatial information is often necessary to identify objects and to specify locations of interest. Objects might be distinguishable in terms of size, such as height or width, and locations might be distinguishable in terms of proximity to salient landmarks or the direction from a starting point. In recent years, much

research has concerned the ability of organisms to represent *geometric* cues, particularly those that characterize the corners of enclosed spatial layouts (e.g., Cheng, 1986; Hermer & Spelke, 1994, 1996; Learmonth, Newcombe, & Huttenlocher, 2001). The task, which involves distinguishing among the corners of an enclosed space, is far from trivial because the appearance of a particular corner depends on the orientation of the space or the point of view of the organism. It has been shown that adults and children (as well as a variety of nonhuman animals) are capable of processing geometric cues from enclosed layouts under a wide range of conditions, but very little is known about the emergence and development of these processes.

OBJECT SIZE

Based on the existing research on the origins of spatial representation, it seems that from an early age, humans are sensitive to a variety of cues necessary for identifying objects (e.g., Baillargeon, 1994; Spelke & Newport, 1998). Baillargeon and Graber (1987), for example, showed that infants are able to represent size information. In their study, infants were presented with short and tall objects that moved behind a screen. The screen contained a window at a particular height so that the taller object, but not the shorter object, should be seen as it moved from one side of the screen to the other. The authors found that 5.5-month-olds expected such a relation to hold true; that is, infants looked significantly longer at the display if the shorter object appeared in the window or if the taller object did not, indicating that they were sensitive to the height of each object.

Using a different paradigm, Baillargeon (1987, 1991) examined the precision with which infants represent height information. In these studies, infants were shown a block, placed behind a screen that rotated along an arc. The rotation of the screen was either consistent or inconsistent with the height of the block behind it. In the consistent case, the screen stopped rotating when it reached the top of the block. In inconsistent cases, the rotation of the screen was unhindered by the block; that is, the screen either rotated a full 180° or partway through the top of the block. The older infants (6.5 months) looked longer at both inconsistent events, whereas the younger infants (4.5 months) only looked longer when the screen rotated the entire way through the block (180°), indicating that younger infants represent object height less precisely than older infants. These studies showed that although infants can represent height information by 4.5 months of age, the nature of the representation changes with development.

Other research conducted by Huttenlocher and colleagues demonstrated that infants represent height in terms of the relation between two objects. In particular, it was shown that infants (5.5–7.5 months) could distinguish between dowels of different height when another object, serving as a standard, was present; they could

not make such distinctions when no standard was available (Duffy, Huttenlocher, Levine, & Duffy, 2005; Huttenlocher, Duffy, & Levine, 2002; see also, Feigenson, Carey, & Spelke, 2002). There is evidence that only when the sizes being compared involve fairly large differences are infants (and older children) capable of making spatial discriminations in the absence of a standard (e.g., Brannon, Lutz, & Cordes, 2006; Huttenlocher et al., 2002).

OTHER SPATIAL-RELATIONAL INFORMATION

The representation of spatial-relational information by infants has been shown in other contexts as well. For example, even newborns are sensitive to the relative positions of distinct, unconnected objects. That is, they can discriminate between pairs of objects when the only difference is the top–bottom positions (e.g., a cross above a square vs. a square above a cross; Antell & Caron, 1985). Quinn and colleagues have also found that spatial-relational sensitivity applies to groups of objects. In particular, there is evidence that infants between 3 and 10 months of age can group stimuli into spatial categories, including above versus below (e.g., Quinn, 1994; Quinn, Cummins, Kase, Martin, & Weissman, 1996), left versus right (e.g., Quinn, 2004), and the relation between (e.g., Quinn, Adams, Kennedy, Shettler, & Wasnik, 2003). Some categories, however, might be more difficult to represent, emerging at different ages during development. For example, in contrast to older infants (6–7 months), the representation of above versus below in younger infants (3–4 months) is specific to the particular objects in the above and below positions (Quinn et al., 1996; Quinn, Polly, Furer, Dobson, & Narter, 2002). Furthermore, whereas 6- to 7-month-olds appear to represent the between relation, 3- to 4-month-olds do not (Quinn, Norris, Pasko, Schmader, & Mash, 1999).

In addition to the spatial relations among unconnected objects, it has been shown that the sensitivity to relational information applies to connected stimuli. For example, there is evidence that even newborns represent the angular size of two line segments. When presented with line segments joined by either an acute or obtuse angle, from different orientations, infants distinguished between these angles, looking longer at the angular relation they had not previously seen (e.g., Cohen & Younger, 1984; Slater, Mattock, Brown, & Bremner, 1991). The stimuli were fairly simple, however; there were only two connected lines (both equal in length), which might have served to highlight the angular relation.

SHAPE AND THE CONSTITUENT PARTS OF ENCLOSED LAYOUTS

Young infants (2–3 months) have also been shown to differentiate stimuli on the basis of shape (e.g., rectangle vs. square, cross vs. triangle) when stimuli are pre-

sented from different orientations (e.g., Schwartz & Day, 1979; Slater, Morison, Town, & Rose, 1985). Further evidence for shape representation comes from studies showing that infants are capable of forming abstract shape categories. For example, different exemplars of triangles are all considered triangles and treated as distinct from exemplars of rectangles (e.g., Bomba & Siqueland, 1983). These data have been taken as evidence that infants encode spatial layouts as holistic forms, even when the entire layout is not perceptually available.

Other research suggests that infants might also be sensitive to the constituent parts of enclosed forms. In a series of experiments, Newcombe and colleagues familiarized infants (5 months) to an object hidden at a particular position in a narrow sandbox 24 in. long. After familiarization, the target object appeared either at the original location or at a different location some distance away. Infants looked longer at the novel distance in the sandbox than the previously familiarized distance, indicating that by 5 months of age, infants are capable of using the distance within an enclosed space to discriminate between locations as close as 8 in. (Newcombe, Huttenlocher, & Learmonth, 1999). The distance information was presented in a fairly simple context, however; the enclosed space was narrow so that distance was only available along a single dimension (x axis).

The constituent parts of an enclosed spatial layout could also involve one or more corners, distinguishable in terms of cues such as the lengths of sides, the size of subtended angles, or both. Such cues have been called *geometric* to contrast them with *nongeometric* cues, which do not involve spatial extent (e.g., Gallistel, 1990). The existing research indicates that there might be conditions when infants are sensitive to particular geometric cues, such as angular size (Slater et al., 1991) and distance (Newcombe et al., 1999). As indicated earlier, these conditions have involved fairly simple contexts where the cue of interest is typically presented in isolation, such as when the sensitivity to angular size is tested by presenting infants with only two line segments (of equal length), and when the sensitivity to relative distance is tested along only one axis. Such conditions rarely exist in our environment, however. Thus, it is important to determine whether infants are also able to represent the relevant geometric cues in more complex cases. Such is the case when distinguishing among the corners of an enclosed layout.

There are several studies showing that 18- to 24-month-olds represent the geometry of enclosed spaces (e.g., Hermer & Spelke, 1994, 1996; Learmonth et al., 2001). The task in these studies typically involves a rectangular room with four identical containers placed at each of the corners. Children stand inside the room and watch as an experimenter hides an object (toy) in one of the containers. After children are shown where the toy is located, they are spun around several times with eyes covered and then allowed to search for the hidden toy. This procedure serves to disorient children, preventing them from simply relying on egocentric information about their own position to locate the hidden object (e.g., "the object in front and to my left"). When there are no landmarks, only geometric cues such as

relative side length can be used to identify the corners. On this task, children tend to search at the two corners with the same spatial relations (e.g., the corners with the longer wall to the left of the shorter wall), indicating that they are capable of using geometric cues to distinguish between corners of an enclosed space.

This geometric sensitivity in children was originally shown in a specific context. Children were tested inside a room shaped like a rectangle where they searched for a hidden object after being spun around several times (with their eyes covered). More recently, it has been shown that this sensitivity to geometric cues might be more general. It applies to a variety of shapes, including an isosceles triangle (Huttenlocher & Vasilyeva, 2003; Lourenco & Huttenlocher, 2006), a rhombus (Hupbach & Nadel, 2005), and an octagon (Newcombe & Ratliff, 2006), and it applies to different viewing positions so that even when children stand outside an enclosed space they can discriminate the corners (Lourenco, Huttenlocher, & Vasilyeva, 2005). There is also evidence that children are sensitive to the geometry of small, nonnavigable spaces (e.g., Huttenlocher & Vasilyeva, 2003; cf. Gouteux, Vauclair, & Thinus-Blanc, 2001) and that there is some geometric sensitivity when the disorientation procedure involves rotating the enclosed space instead of the viewer (Lourenco & Huttenlocher, 2006; cf. Gouteux, Vauclair, & Thinus-Blanc, 2001). Other studies with adults and nonhuman animals provide evidence that geometric cues are also extracted from two-dimensional enclosed layouts presented on a computer screen (Kelly & Spetch, 2004a, 2004b). It should be noted that although the sensitivity to geometry has been shown in a variety of contexts, there might be important differences (discussed later) in how geometry is represented across context.

THIS STUDY: THE GEOMETRY OF AN ENCLOSED LAYOUT (ISOSCELES TRIANGLE)

In this study, we examined whether young infants could use geometric cues from an enclosed layout to differentiate among its corners. That several species of nonhuman animals (e.g., rats: Cheng, 1986; chicks: Tommasi & Polli, 2004; Vallortigara, Zanforlin, & Pasti, 1990; pigeons: Kelly, Spetch, & Heth, 1998; rhesus monkeys: Gouteux, Thinus-Blanc, & Vauclair, 2001; tamarins: Deipolyi, Santos, & Hauser, 2001; fish: Sovrano, Bisazza, & Vallortigara, 2002; Vargas, Lopez, Salas, & Thinus-Blanc, 2004; for review, see Cheng & Newcombe, 2005) are sensitive to the geometry of enclosed spaces suggests at least two possibilities concerning the origins of this sensitivity in humans. One possibility is that there are homologous mechanisms available relatively early in life, although this would not guarantee identical developmental paths for different species. Another possibility is that commonalities across species arise from similar experiences, necessary for their emergence. Although there might be a variety of important experiences, inde-

pendent locomotion has been shown to affect performance on at least some spatial tasks (e.g., Bai & Bertenthal, 1992; Bertenthal, Campos, & Barrett, 1984; Campos et al., 2000). Because 18- to 24-month-olds and nonhuman animals have had extensive experience actively moving around in their respective environments, it remains unknown whether the mechanisms necessary for representing the geometry of enclosed layouts are functional prior to such experience.

To test whether young infants (approximately 5.5 months of age), who have likely had little (if any) experience with independent locomotion, are sensitive to the geometry of an enclosed layout, we adapted the canonical task in which organisms search for a target object at one of the corners of a space. The primary difference involved the response measure. Because the goal here was to examine the encoding of geometric information from an enclosed layout, rather than the ability to use this information to guide the search for a target object, a looking-time procedure was used. As in other studies with looking-time procedures, there was a habituation phase followed by a set of test trials.

During the habituation phase, infants were presented with a two-dimensional outline of an isosceles triangle. The isosceles triangle shape, which has been used with older children (Huttenlocher & Vasilyeva, 2003; Lourenco & Huttenlocher, 2006), is especially informative with respect to geometric sensitivity because, unlike other shapes (e.g., rectangle or rhombus), it includes multiple geometric cues, namely, angular size and side lengths. As noted earlier, it is rarely the case in the real world that particular geometric cues are presented in isolation. A two-dimensional form was used to ensure that each corner could be viewed equally well. Many studies testing geometric sensitivity have used three-dimensional spaces (e.g., rooms and models), but, importantly, Kelly and Spetch (2004a, 2004b) showed that adult humans and pigeons also encode the geometry of two-dimensional layouts. Although there could be important differences, it has been suggested that mobile organisms treat two- and three-dimensional spaces similarly on certain location tasks, perhaps drawing on the same foundational processes (e.g., Kelly & Spetch, 2004a, 2004b; Saucier et al., 2002; Spetch, Cheng, & MacDonald, 1996; Spetch et al., 1997).

In this study, the target corner was marked by a red dot. The triangle appeared from different orientations with the dot in one of the corners. The different orientations ensured that only geometric cues about the shape of the enclosed layout could be used to distinguish the corners. Other information, such as the target's position in relation to the viewer's body, would not allow for such discriminations. In Experiment 1, the orientations were highly variable, sampled across 360°; in Experiment 2, the orientations were less variable, restricted to within 180°.

The habituation phase continued until the duration of infants' responses (i.e., looking times) decreased to a criterion. During the test phase, the isosceles triangle continued to appear from different orientations, but the dot alternated between the familiar corner (i.e., the target corner during habituation) and a novel corner (i.e.,

one of the other two corners). The logic of this procedure is that once infants habituate, their looking times should be longer for stimuli appearing novel than for stimuli appearing familiar.

EXPERIMENT 1: HIGHLY VARIABLE ORIENTATIONS

Method

Participants. The sample consisted of 56 healthy full-term infants between 4.5 and 6.5 months of age ($M = 5.5$ months, $SD = 0.64$ months). Across all groups, the average age was comparable (see Results), and there were equal numbers of boys and girls. The data from an additional 4 infants (3 girls, 1 boy) were not included in the analyses because these infants did not complete the experiment. Although demographic information was not collected systematically, infants appeared to come from a variety of ethnic and socioeconomic backgrounds.

Stimuli. Infants were shown an isosceles triangle on a computer screen (32 cm \times 23 cm). The triangle consisted of two sides measuring 8.5 cm, and one side measuring 4.5 cm. As shown in Figure 1, the unique corner has two sides of equal length, and a smaller angle than the other two corners. The two nonunique corners, which consist of unequal-length sides and have the bigger (same-sized) angle, are distinguishable by the relative positions of the long and short sides (e.g., the corner with the longer side to the left of the shorter side vs. the corner with the shorter side to the left of the longer side); we refer to these corners as nonunique corner A and nonunique corner B (see Figure 1). The target dot, which always appeared at one of the triangle's corners, was bright red and measured 5 mm in diameter.

Procedure. Each infant was tested in a single session lasting approximately 15 min. The experiment took place inside a large booth covered in black felt with two cutouts, one for the screen of the computer monitor and one for the lens of a camcorder. The infant sat on his or her parent's lap facing the computer screen at a distance of approximately 30 cm. Parents were instructed to look away from the computer screen so as not to influence infants' behavior.

To capture infants' attention, the stimulus (triangle with dot) appeared on the computer screen immediately following a "ding" sound emitted from speakers outside the booth and placed behind the monitor. Infants could be seen on another computer monitor (via video feed from the camcorder) placed outside the booth. An experimenter, who sat outside the booth and was naive to the stimulus on each trial, recorded when infants looked at the stimulus by pressing the spacebar on the computer keyboard, which activated the timing program. The total looking time for each trial was calculated online by the timing program. The

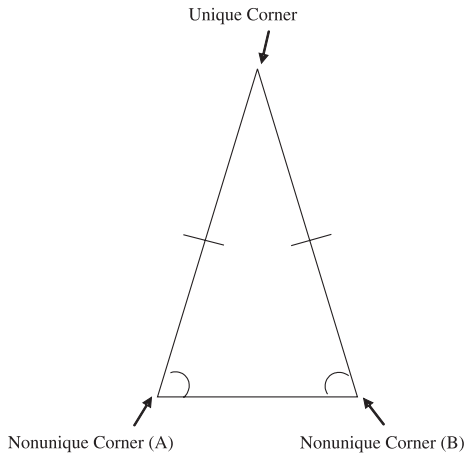


FIGURE 1 An illustration of the isosceles triangle used in this study. The triangle contains two sides that are equal in length (indicated by perpendicular lines) and that are longer than the other side. There are two angles that are equal in size (indicated by half-circles) and that are bigger than the other angle. The corner with the equal-length sides and smaller angle is referred to as the unique corner. The other two corners with unequal-length sides and bigger angle are referred to as the nonunique corners (A and B).

stimulus on each trial remained on the computer screen for a maximum of 10 sec, regardless of whether infants looked at the stimulus for the entire length of the trial.

Across trials, the stimulus (triangle with dot) was presented from different orientations and was always centered on the computer screen. As shown in Figure 2, there were eight possible orientations. The orientation on a given trial was randomly determined, with the only restriction being that each orientation was sampled once before any repetitions occurred.

The habituation phase lasted until the criterion was met: a 50% decrease in looking times over three consecutive trials relative to the first three trials, or a maximum of 16 trials. During the habituation phase, the red dot remained in the same corner of the isosceles triangle. Eight test trials followed this phase. There was no break between habituation and test phases; the computer timing program, which calculated when the habituation criterion had been reached, automatically began the test phase. The test phase was identical to the habituation phase except that the red dot alternated between the corner infants saw during habituation (familiar corner) and a different corner (novel corner). The reliability of looking time recordings for all trials (habituation and test) was computed based on agreement or disagreement between two observers, both blind to the stimuli, at each 100-msec interval; reliability was 92% across all infants.

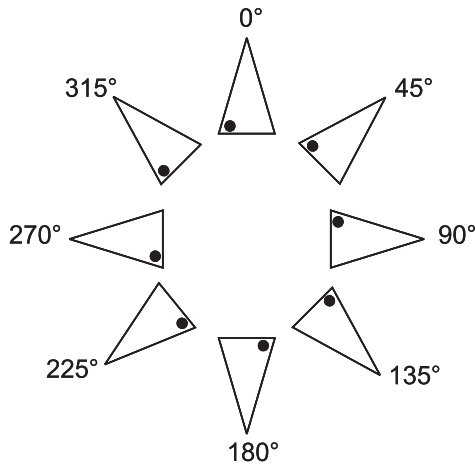


FIGURE 2 The eight possible orientations used in Experiment 1. This example includes the target dot, which was bright red, at nonunique corner A.

Design. Infants were randomly assigned to one of two types of habituation corners. Specifically, for half the infants, the dot appeared at the unique corner, and for the other half, the dot appeared at one of the nonunique corners (either nonunique corner A or nonunique corner B) throughout the habituation phase. The contrasting corner on the test trials was fully counterbalanced; for example, for infants who saw the dot at the unique corner during habituation, the novel corner was nonunique corner A for half the infants and nonunique corner B for the other half. There were two conditions in this experiment. In one condition, the comparison during the test trials was between the unique corner and a nonunique corner (32 infants). In another condition, the comparison was between the two nonunique corners (24 infants).

Results

Figure 3 shows the mean looking times on the habituation and test trials for the two conditions (i.e., unique vs. nonunique corner comparison, and the two nonunique corners comparison). An analysis of infants' ages revealed that the mean age in each condition was comparable ($M = 5.49$ months, $SD = .60$ months, and $M = 5.52$ months, $SD = .69$ months, respectively), $F(1, 54) = .038$, $p > .1$.

To determine whether infants' looking times changed during the habituation phase, an analysis of variance (ANOVA)—which included habituation trials (two sets of trials: first three and last three) as the within-subjects variable, and condition (unique vs. nonunique corner comparison, or the nonunique corners compari-

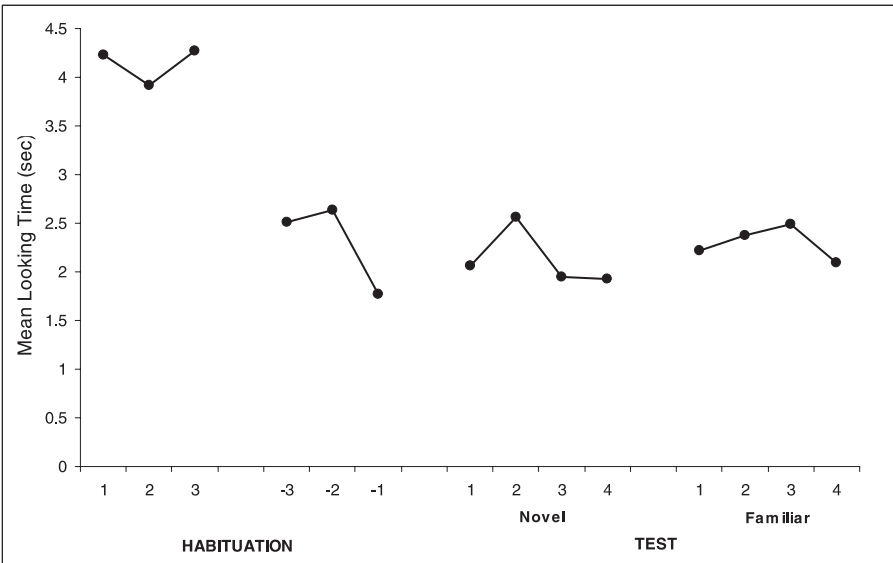
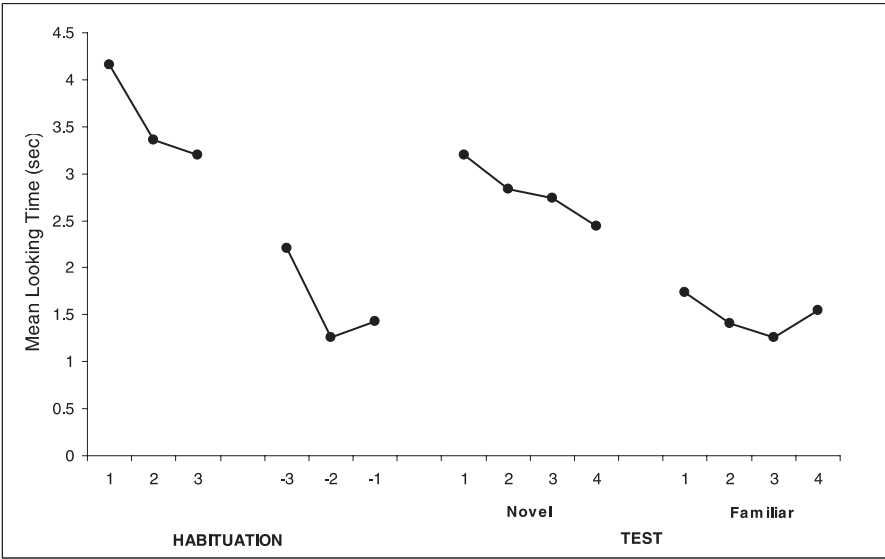


FIGURE 3 Mean looking times (sec) for habituation and test trials in Experiment 1. The first three (1, 2, 3) and last three (-3, -2, -1) habituation trials are shown. The four novel test trials and the four familiar test trials are also shown. The top panel depicts the results for the condition comparing the unique corner and a nonunique corner. The bottom panel depicts the results for the condition comparing the two nonunique corners.

son) and habituation corner (unique corner, nonunique corner A, or nonunique corner B) as the between-subject variables—was conducted; the dependent variable was raw looking times. There was a significant main effect of habituation trials, $F(1, 51) = 68.68, p < .001, \eta_p^2 = .574$, but no other main effects or interactions ($ps > .1$); infants' looking times significantly decreased during the habituation phase, regardless of condition and habituation corner (first set of habituation trials: $M = 3.9$ sec, $SD = 1.7$ sec; last set of habituation trials: $M = 1.9$ sec, $SD = 1.2$ sec). The mean number of habituation trials was 10.4 trials ($SD = 4.1$ trials).

Additional analyses were conducted on the test trials (i.e., four novel test trials and four familiar test trials). A preliminary ANOVA on raw looking times with age (median split) and sex as the between-subject variables revealed no significant main effects or interactions of age and sex ($ps > .1$). The results were similar when only the first test trial of each type (i.e., first novel test trial and first familiar test trial) was used in the analysis ($ps > .1$). Accordingly, age and sex were not analyzed further.

To determine whether infants' looking times during the test trials differed across the two conditions, an ANOVA, which included type of test trials (novel vs. familiar) as the within-subjects variable and condition (unique vs. nonunique corner comparison, or the nonunique corners comparison) as the between-subject variable, was conducted on raw looking times. There was a significant main effect of test trials, $F(1, 54) = 16.53, p < .001$, and, more important, there was also a significant interaction of condition and test trials, $F(1, 54) = 34.71, p < .001, \eta_p^2 = .391$. Follow-up analyses revealed that for the unique versus nonunique corner comparison, looking times during the novel test trials were longer than those during the familiar test trials (novel test trials: $M = 2.9$ sec, $SD = 1.2$ sec; familiar test trials: $M = 1.4$ sec, $SD = .8$ sec), $t(31) = 6.82, p < .001$, two-tailed. In contrast, for the nonunique corners comparison, there was no difference in looking times during novel and familiar test trials, $t(23) = -1.47, p > .1$, two-tailed. These analyses indicate that infants are able to discriminate between the unique corner and a nonunique corner but not between the two nonunique corners.

To determine whether looking times during the novel test trials and the last set of habituation trials differed, an ANOVA with experimental phase (habituation and test) as the within-subjects variable was conducted on raw looking times for each condition. For the unique versus nonunique corner comparison, there was a significant effect of experimental phase, $F(1, 31) = 24.96, p < .001, \eta_p^2 = .446$; that is, infants' looking times during novel test trials were longer than those during the last set of habituation trials (novel test trials: $M = 2.9$ sec, $SD = 1.2$ sec; last habituation trials: $M = 1.6$ sec, $SD = 0.9$ sec). In contrast, for the nonunique corners comparison, there was no difference in looking times between the novel test trials and the last set of habituation trials ($p > .1$). These analyses confirm that discriminating the unique corner from a nonunique corner is easier for infants than discriminating between two nonunique corners.

Additional looking time analyses for the unique versus nonunique corner comparison revealed that the majority of infants in this condition (23 out of 32 infants; binomial test, $p < .05$) had longer looking times on the novel test trials (relative to the last set of habituation trials). Other analyses revealed that infants' ability to discriminate between the unique corner and a nonunique corner did not depend on which corner served as the target during habituation ($p > .1$). That is, infants were as likely to make this distinction whether the target during habituation was the unique corner or a nonunique corner. It should also be noted that these effects, and those earlier, were similar when only the first test trial of each type was used in the analyses.

Discussion

In this experiment, we tested whether infants might be able to use geometric cues from an enclosed layout shaped like an isosceles triangle to distinguish among the corners of the triangle. To ensure that discriminations were made on the basis of geometric cues, rather than egocentric information, the isosceles triangle appeared from a variety of orientations. It was found that although infants could discriminate the unique corner from a nonunique corner, they could not discriminate the two nonunique corners. That infants were unable to distinguish among all the corners of an isosceles triangle is consistent with existing research showing that the nature of geometric representation might depend on particular task variables.

According to Kelly and Spetch (2004a, 2004b), one potentially important variable concerns the plane of orientation of the depicted layout. In studies with human adults and pigeons, they concluded that organisms have more difficulty distinguishing between the corners of a rectangular layout if the rectangle is presented vertically (on a computer screen) than if it is laid out horizontally (as with a room). The nonunique corners of an isosceles triangle, which were indistinguishable to infants in this experiment, are similar to the corners of a rectangle in that they differ in terms of the relative positions of the long and short sides (i.e., longer side to the left of shorter side vs. shorter side to the left of longer side).

Although a vertically orientated surface can certainly provide directional information, potentially affecting how the geometry of an object or space is represented, there could be other factors affecting representation. Another factor is whether the task involves movements of the viewer versus movements of the enclosed layout. Recently, Lourenco and Huttenlocher (2006) showed that when a disorientation procedure involved rotating an enclosed space shaped like an isosceles triangle, toddlers could not differentiate between the nonunique corners of the space; yet they could make this distinction when the procedure involved rotating the viewer. Because Lourenco and Huttenlocher used a three-dimensional en-

closed space laid out in the horizontal plane (i.e., a roomlike space), not a two-dimensional layout presented vertically (as in Kelly & Spetch [2004a, 2004b] as well as this experiment), we would suggest that the difficulty experienced by infants was due to the apparent rotational change of the triangle, rather than the vertical plane of presentation or the two-dimensional quality of the enclosed layout.

It is generally reported that tasks involving movements of an object or a space are more difficult than tasks involving movements of the viewer (e.g., Huttenlocher & Presson, 1979; Lourenco & Huttenlocher, 2006; Simons & Wang, 1998; Wraga, Creem, & Proffitt, 2000). This dissociation, which occurs under a variety of conditions, has been taken as evidence that people use different strategies to deal with changes in their relation to the environment. Lourenco and Huttenlocher (2006), for example, suggested that the approach young children used to distinguish among the corners in an enclosed space depended on whether the disorientation procedure involved viewer or space movement. In the viewer movement version, the change in the child's relation to the space was consistent with expectations about how such changes should occur. That is, it is typically the case that one's point of view is altered by movements of one's self, not by movements of a surrounding space. In the space movement version of the task, changes in viewpoint were not consistent with a stationary child. As a result, the task of distinguishing among the corners of an enclosed layout, which changes orientation, involves somehow accounting for these unexpected changes (e.g., Diwadkar & McNamara, 1997; Shelton & McNamara, 2004; Ullman, 1989).

How might one account for changes in the orientation of an enclosed stimulus? One way would be to rely on the invariant properties of the stimulus; that is, the properties of objects or spaces that do not depend on orientation or other transformations (e.g., Biederman & Bar, 1999; see also Logothetis & Sheinberg, 1996; Ullman, 1989). In an isosceles triangle, these properties are the size of the angles and the lengths of the sides. If infants relied exclusively on either of these properties, they would not have to compensate for changes in the triangle's orientation because angular size and side length do not vary with orientation. The invariant information would allow infants to discriminate between the unique corner and a nonunique corner because both corners differ in the size of the angles and in the lengths of the sides. That is, the unique corner has a smaller angle than the other two corners, and is connected by two sides equal in length rather than two sides unequal in length. Such invariant information would make it impossible to distinguish between the two nonunique corners as both of these corners are identical in angular size and have two unequal-length sides.

Another way to differentiate the corners of a stimulus shaped like an isosceles triangle would be to use information about the entire shape of the triangle, which includes the relative positions of the adjoining long and short sides. Although such information can be used to distinguish between the nonunique corners, it is not in-

variant with respect to orientation. That is, information about relative position depends on the orientation of the stimulus. To illustrate, consider the 90° and 270° orientations in Figure 2. The target dot is at the same nonunique corner of the triangle, but the relative positions of the long and short sides differ for each orientation; at 90° , the shorter side is to the left of the longer side, and at 270° , the longer side is to the left of the shorter side. As a result, it is only possible to distinguish between the nonunique corners if one can compensate for the changing relation of the different-length sides. This process of compensating for variable geometric cues might involve aligning information about the triangular layout available on the most recent trial with information about the layout stored in memory from a previous trial. Because of the highly variable nature of these geometric cues, the corresponding mental alignment processes were likely extensive and clearly beyond the capabilities of young infants.

EXPERIMENT 2: LESS VARIABLE ORIENTATIONS

In the second experiment, we examined whether infants might be able to distinguish between the nonunique corners of an isosceles triangle if the triangle was presented from less variable orientations. Earlier, we suggested two possible strategies for dealing with a task that involves changes in the orientation of an enclosed layout shaped like an isosceles triangle. Infants could rely on the invariant properties of the triangle, which would allow the unique corner to be distinguished from a nonunique corner but would make it impossible to distinguish between the two nonunique corners. Alternatively, infants could rely on information about the entire shape of the isosceles triangle, which includes the relative positions of the adjoining long and short sides. Although the latter approach allows for distinguishing between the nonunique corners, it requires accounting for changes in the triangle's orientation because information about relative positions is orientation specific. As noted earlier, to account for orientation changes, viewers might mentally align currently perceivable information with information stored in memory.

To distinguish between these two alternatives, the range of possible orientations was restricted to within 180° . If only the invariant properties of the triangle are used on this task, infants would still be unable to distinguish between the nonunique corners because these corners have the same-sized angle and unequal-length sides. However, if infants rely on information about the entire shape of the triangle, they might be able to distinguish between the nonunique corners in this experiment because less variable orientations would require less extensive mental alignment (e.g., Just & Carpenter, 1985; Shepard & Cooper, 1986; Shepard & Metzler, 1971).

Method

Participants. The sample consisted of 48 healthy full-term infants between 4.6 and 6.5 months of age ($M = 5.58$ months, $SD = .59$ months). The data from an additional 11 infants were not analyzed because these infants did not complete the experiment (8 boys, 3 girls). As in the previous experiment, infants appeared to come from a variety of ethnic and socioeconomic groups, although demographic information was not collected systematically.

Stimuli, design, and procedure. This experiment was identical to Experiment 1, except for the following exceptions. First, the eight possible orientations were restricted to within 180° , either from the left or right side of a vertical axis (see Figure 4), or from the top or bottom side of a horizontal axis. Note that like the previous experiment, the stimulus (triangle with dot) was always centered on the computer screen. Second, because infants in the previous experiment (where the orientations were highly variable) could distinguish the unique corner from a nonunique corner, here we only compared the two nonunique corners. Thus, during the habituation phase, half the infants saw the dot at nonunique corner A and half the infants saw the dot at nonunique corner B. During the test phase, the dot always alternated between the two nonunique corners. As in the previous experiment, reliability for infants' looking times on habituation and test trials was based on agreement or disagreement between two observers at each 100-msec interval. Reliability was 93% across all infants.

Results and Discussion

Figure 5 shows the mean looking times on the habituation and test trials in this experiment. To determine whether infants' looking times changed during the habituation phase, an ANOVA—which included habituation trials (two sets of trials: first three and last three) as the within-subjects variable, and habituation corner (nonunique corner A or nonunique corner B) and type of orientation group (orientations left or right of vertical axis or orientations top or bottom of horizontal axis) as the between-subject variables—was conducted; the dependent variable was raw looking times. There was a significant main effect of habituation trials, $F(1, 44) = 32.02$, $p < .001$, $\eta_p^2 = .421$, but no other main effects or interactions ($ps > .05$); looking times decreased during the habituation phase, regardless of habituation corner and type of orientation group (first set of habituation trials: $M = 3.9$ sec, $SD = 1.9$ sec; last set of habituation trials: $M = 2.3$ sec, $SD = 1.5$ sec). The average number of habituation trials was 11.3 trials ($SD = 4.0$ trials).

Another set of analyses involved the test trials (i.e., four novel test trials and four familiar test trials). To determine whether infants' looking times during novel and familiar test trials differed, an ANOVA—which included type of test trials

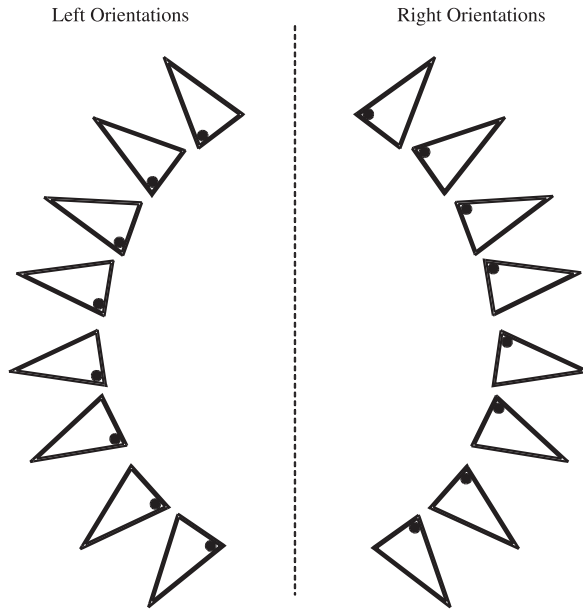


FIGURE 4 The less variable orientations used in the “vertical axis” group in Experiment 2. Note that infants only saw the orientations on either the left or right side of this vertical axis. The vertical axis was not present during testing.

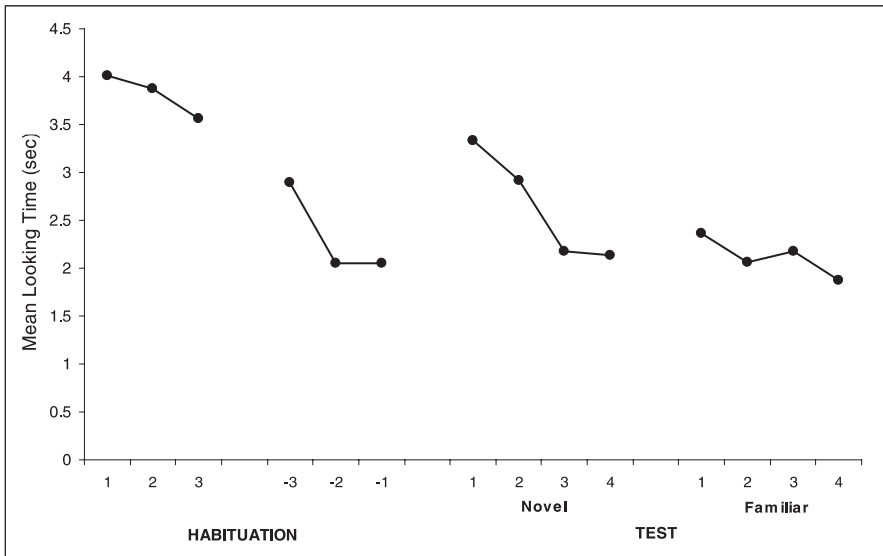


FIGURE 5 Mean looking times (sec) for the habituation and test trials in Experiment 2.

(novel and familiar) as the within-subjects variable, and age (median split), sex, and type of orientation group (vertical axis or horizontal axis) as the between-subject variables—was conducted on raw looking times. There was a significant main effect of test trials, $F(1, 40) = 5.10$, $p < .05$, $\eta_p^2 = .113$, but no other main effects or interactions ($ps > .05$), indicating that infants distinguished between the two nonunique corners, regardless of age, sex, or type of orientation group (novel test trials: $M = 2.7$ sec, $SD = 1.5$ sec; familiar test trials: $M = 2.1$ sec, $SD = 1.1$ sec). The same pattern of results was obtained when only the first test trial of each type (i.e., first novel test trial and first familiar test trial) was used in the analysis.

To determine whether looking times during the novel test trials and the last set of habituation trials differed, an ANOVA with experimental phase (habituation and test) as the within-subjects variable was conducted on raw looking times. (Because age, sex, and type of orientation group were not significant in the preceding analyses, these variables were not included here.) Although experimental phase was not significant when all of the novel test trials were used in the analysis ($p > .05$), experimental phase was significant when only the first novel test trial was used, $F(1, 47) = 8.55$, $p < .01$, $\eta_p^2 = .154$. These results indicate that when performance was not affected by subsequent test trials, infants' looking times on the first novel test trial were longer than those during the last set of habituation trials (first novel test trial: $M = 3.4$ sec, $SD = 1.9$ sec; last habituation trials: $M = 2.2$ sec, $SD = 1.3$ sec), confirming that infants distinguished between the nonunique corners of the isosceles triangle. Additional analyses revealed that the majority of infants (31 out of 48 infants, binomial test, $p < .05$) had longer looking times on the first novel test trial (relative to the last set of habituation trials).

The results from this experiment indicate that when the isosceles triangle appeared in orientations that were restricted to within 180° , infants were able to discriminate between the nonunique corners. Earlier, it was suggested that if such a distinction was made, it would show that infants had not relied exclusively on the invariant properties of the isosceles triangle. It is worth noting, however, that there is another invariant relation, not discussed previously, that could have served as the basis for the discrimination. Restricting the range of orientations had the effect of creating a constant allocentric frame of reference, and, recently, it has been suggested that the allocentric frame of reference constitutes the default relational encoding strategy in primate species (Haun, Rapold, Call, Janzen, & Levinson, 2006). As can be seen in Figure 4, the nonunique corners are distinguishable via their relatively consistent top-down relation. (In the group where orientations appeared either on the top or bottom side of the horizontal axis, the nonunique corners were mostly in a left-right relation.) It would be possible to use the allocentric relation to differentiate between these two corners if infants focused exclusively on the nonunique corners, which they might have done given the perceptual similarity of these two corners. Based on the results of Experiment 1, however, it seems unlikely that infants used this approach to solve the discrimination problem. In Ex-

periment 1, infants distinguished between the unique corner and a nonunique corner regardless of which corner served as the target during habituation; if they had focused on the nonunique corners, they should have had difficulty making the unique versus nonunique corner distinction when the nonunique corner served as the target.

Having ruled out the possibility that infants relied on particular invariant properties or relations to distinguish between the nonunique corners, it would seem that they were able to make this distinction by representing information about the entire shape of the enclosed layout, which includes the relative positions of the short and long sides. This information is orientation specific, and, as such, requires that viewers compensate for the changes in rotational alignment. In contrast to the previous experiment, the orientations were less variable and the corresponding mental transformations were necessarily less extensive, thereby allowing infants to distinguish between the two nonunique corners of the isosceles triangle.

GENERAL DISCUSSION

Previous research has shown that older children and nonhuman animals are capable of representing the geometry of an enclosed layout. Under a variety of conditions, they use geometric cues to distinguish among particular constituent parts (corners) of enclosed spaces (e.g., Cheng, 1986; Hermer & Spelke, 1996; Kelly & Spetch, 2004b). The goal of this study was to determine whether young infants, too, are sensitive to the geometric cues available in an enclosed layout. To this end, we adapted the procedures used in previous studies to test whether infants could distinguish among the corners of an isosceles triangle. To prevent infants from relying on egocentric information, the isosceles triangle was presented from different orientations. It was found that when the orientations were highly variable (i.e., sampled across 360°), infants distinguished the unique corner from a nonunique corner, but they could not distinguish between the two nonunique corners. Importantly, however, when the orientations were less variable (i.e., restricted to within 180°), infants did distinguish between the nonunique corners of the isosceles triangle. That young infants could only discriminate between particular corners under certain conditions has important implications for understanding the processing of geometric cues.

How Are Geometric Cues Represented?

There is evidence that the representation of enclosed layouts (objects and spaces) is specific to particular viewpoints (e.g., Diwadkar & McNamara, 1997; Presson, DeLange, & Hazelrigg, 1987; Tarr, Williams, Hayward, & Gauthier, 1998). When circumstances bring about changes to one's point of view, either because the or-

ganism moves or the orientation of the layout is altered, organisms must account for such changes, mentally aligning currently perceivable information with information previously perceived and stored in memory (e.g., Diwadkar & McNamara, 1997; Ullman, 1989). The existing research indicates that the process of accounting for changes in viewpoint might depend on a variety of task variables, including how movements occur and the extent of these movements.

Tasks involving movements of the viewer appear to invoke brain mechanisms distinct from those invoked by tasks involving movements of an object or other aspects of the spatial environment (e.g., Kosslyn, Ganis, & Thompson, 2001; Kosslyn, Thompson, Wraga, & Alpert, 2001; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999; Zacks, Vettel, & Michelon, 2003). It has also been suggested that people adopt different strategies for dealing with each type of task (e.g., Huttenlocher & Presson, 1979; Presson, 1982; Wraga et al., 2000). Consider each task. When viewers change position, they need only account for one moving item: the viewer himself or herself. In contrast, when the environment is altered, viewers generally have to account for the (relative) positions of several items. These items could be different objects in an array, or the constituent parts of an object or enclosed spatial layout (Lourenco & Huttenlocher, 2006; see also, Huttenlocher & Presson, 1979; Wraga et al., 2000).

In this study, the enclosed layout was presented from different orientations such that the task required somehow accounting for the apparent rotational change. Earlier, we suggested different strategies for solving this task. One possibility would be to rely on the invariant properties of the enclosed layout (e.g., Biederman & Bar, 1999); that is, the properties that remain constant across variable orientations. Although such an approach certainly has the effect of simplifying the task (because mental alignment processes need not be invoked), it also has the effect of reducing accuracy. For example, if the invariant geometric cues are used, it is only possible to distinguish the unique corner from a nonunique corner in the isosceles triangle. It is not possible to distinguish between the two nonunique corners, both of which are identical in angular size and both of which have unequal-length sides. This approach would be especially problematic for an enclosed layout shaped like a rectangle where only information about relative side lengths is available to distinguish between corners.

Another way to solve a task where the enclosed layout changes orientation would be to rely on information about the entire shape of the layout. In this case, the relative positions of the different-length sides are also represented. Because such relational information varies with the orientation of the layout, it requires that viewers compensate for changes in orientation by mentally aligning the relevant cues. The process of mental alignment would serve to increase the accuracy of responses by allowing finer discriminations to be made. This is clearly the case for an isosceles triangle and would also be the case for a rectangle where only relative side length can be used to identify corners.

Increased accuracy in this task would also occur if viewers formed separate categories for each of the corners of the enclosed layout. It is possible that with less variable orientations (as in Experiment 2), infants developed more exclusive categories so that rather than two categories of unique and nonunique, they might have relied on three categories with each nonunique corner constituting a separate category (e.g., Oakes, Coppage, & Dingel, 1997; Oakes & Spalding, 1997). Such a representation would include a set of exemplars for each category, reducing the need to account for differences in orientation. Although this possibility was not directly tested in this study, one reason to believe that infants actually represented the entire layout as a connected (enclosed) form, rather than as separate categories for three corners, is that even when stimuli are perceptually incomplete, infants have been shown to represent those stimuli as connected forms (Bomba & Siqueland, 1983; Schwartz & Day, 1979). Such forms are typically orientation specific so that on tasks where orientation varies, viewers have to compensate for the variation via particular mental transformation processes.

It should be noted that mental transformations are not all of comparable difficulty. For example, people are faster and more accurate on mental rotation tasks when the items being compared are closer in orientation (e.g., Just & Carpenter, 1985; Shepard & Cooper, 1986; Shepard & Metzler, 1971). The ability to engage in such transformations might also depend on the complexity of the enclosed layout (e.g., symmetrical vs. asymmetrical shapes) and the presence of identical corners (as with rectangles). Nevertheless, our results suggest that in some cases, such as when an isosceles triangle is presented from a limited range of orientations, even infants can process the relevant geometric cues (see also Hespos & Rochat, 1997; Rochat & Hespos, 1996). The processes invoked by infants, however, might not be identical to those invoked by older children and nonhuman animals. There might be characteristic differences that depend on the type of behavioral response required by the task (e.g., looking vs. searching; Hood, Carey, & Prasada, 2000; Hood, Cole-Davis, & Dias, 2003) and particular experiences over the course of development.

Origins of Geometric Representation

The 5.5-month-olds in this study were capable of using geometric cues to distinguish among the corners of an enclosed layout. Although infants of this age have little or no experience locomoting independently in the world, they have had access to other (potentially important) experiences. For example, there is evidence that seeing how objects move about in space (relative to one's own body as well as to other objects) influences the encoding of distance information (e.g., Campos et al., 2000). Another potentially important experience concerns the emergence of independent sitting, which has been shown to relate to the perceived reachability of distal objects (Rochat & Goubet, 1995; Rochat, Goubet, & Senders, 1999). Although the effects of

such experiences were not tested directly in this study, it is likely that they have some influence on infants' ability to represent the geometry of enclosed layouts.

Does this mean that experience with independent locomotion is unrelated to the processing of geometric cues? Not necessarily. The stimuli used in this study were two-dimensional and did not afford navigation. It is possible that locomotory experience might be more directly relevant to representations of three-dimensional spaces, especially those that allow for navigation. Although there is evidence that organisms treat two- and three-dimensional spaces similarly in some cases (e.g., Kelly & Spetch, 2004a, 2004b), there is also evidence that the corresponding representations might be distinct in particular ways (Foster, Castro, & McNaughton, 1989; Weatherford, 1985). For example, it has been suggested that larger, navigable spaces invoke *primary* representations, which might be less susceptible to variations in viewpoint, and that smaller, nonnavigable spaces invoke *secondary* representations, which are highly influenced by point of view (Presson & Hazelrigg, 1984). It is also possible that locomotory experience might serve to enrich early geometric representations, which might not yet generalize to all types of objects and spaces.

CONCLUSIONS

Although previous research has shown that infants are sensitive to geometric cues, this sensitivity is often demonstrated in highly simple contexts. The findings from this study show that by around 5.5 months of age, humans can use the relevant geometric cues from an enclosed layout under variable viewing conditions to distinguish among the corners of the layout. It makes a great deal of adaptive sense that evolution would select for sensitivity to geometry. Geometric information about shape is arguably one of nature's most enduring properties (Gallistel, 1990), and the sensitivity to this information might serve as the foundation for abilities that require the use of geometry, such as identifying objects and determining location (Dehaene, Izard, Pica, & Spelke, 2006).

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