

The Influence of Cue Reliability and Cue Representation on Spatial Reorientation in Young Children

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Previous studies of children's reorientation have focused on cue representation (e.g., whether cues are geometric) as a predictor of performance but have not addressed cue reliability (the regularity of the relation between a given cue and an outcome) as a predictor of performance. Here we address both factors within the same series of experiments. We show that for 18- to 30-month-olds, high cue reliability is a dominant factor positively affecting reorientation behavior. Under conditions of high cue reliability, children use both scalar and nonscalar cues for successful reorientation. By contrast, under conditions of low cue reliability, children successfully use scalar cues but not nonscalar cues, suggesting that mapping of left–right visual features onto a viewer-centric sense of left and right is facilitated when features themselves are ordered. More generally, we suggest that cue-driven spatial reorientation is best understood as part of a broader system capable of flexibly linking stimuli and responses.

INTRODUCTION

To locate important objects and places, mobile animals must code and retain spatial information in a way that accommodates self-movement and variation in point of view. A task used to explore this process is the “reorientation task,” in which an individual typically sees an object hidden in a corner of a rectangular room, is spun around with eyes covered, and then searches for the hidden object. It has been argued that the geometry of a search space (e.g., relative wall length) is critical to success in locating a hidden object (for both humans in this paradigm and animals when trained to locate a hidden object via visual cues). Comprehensive reviews by Cheng and Newcombe (2005), Cheng (2008), and Twyman and Newcombe (2010) have generally supported the claim. However, recent findings indicate that reorientation also may occur with certain types of visual cues even when the geometry of the space is held constant (e.g., in a square enclosure). Notably, Huttenlocher and Lourenco (2007) and Lourenco, Addy, and Huttenlocher (2009) found successful reorientation in a square room with figural cues on the enclosure walls. These cues were either

scalar, varying along one dimension such as size (e.g., smaller figures on one wall alternating with larger figures on adjacent walls), or nonscalar, whereby variations extend to distinct categories such as shapes (e.g., figures of one shape on one wall alternating with figures of another shape on adjacent walls). When cues were scalar, children performed above chance, choosing either the hiding corner, or the identically marked, diagonally opposite corner. When cues were nonscalar, children performed at chance. The authors concluded that young children (18 to 24 months old) are reliably able to use scalar cues when reorienting and that this principle subsumes previous claims about the geometry of a surrounding space. That is, relative differences in environmental geometry (such as wall length) can be understood in terms of differences in scalar cues. Importantly, because square enclosures were used, in which figural—and not environmental geometric—differences in scalar information were the only available cues (Huttenlocher & Lourenco; Lourenco et al.), it is difficult if not impossible to make the opposite case. Thus, the more general principle that accounts for the greater breadth of data is that children rely on relative scalar cues, be they figural (e.g., differences in the relative size of cues printed on the surrounding walls) or “geometric” (as in the geometry of the environment, such as differences in relative wall length). We adopt this view in the current work.

Scalar stimuli are inherently ordered, and this ordinality can be represented spatially (Bueti & Walsh, 2009; Hubbard, Piazza, Pinel, & Dehaene, 2005; Huttenlocher, 1967). Adult humans tend to show a left–right bias for ordinal information (Gevers, Reynvoet, & Fias, 2003; Previtali, de Hevia, & Girelli, 2010), with faster responses to items presented in the left visual field that occur earlier versus later in the ordinal sequence (and the opposite pattern for items shown in the right visual field). This bias has also been recently demonstrated in domestic newborn chicks, suggesting the bias may be present quite early in human development (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Vallortigara, Vallini, & Regolin, 2011), especially given that processing of scalar information more generally follows similar principles across a wide range of even quite primitive species (Bisazza, Piffer, Serena, & Agrillo, 2010). Thus, it seems plausible that children are able to capitalize on the possibility of representing scalar stimuli spatially. For instance, when looking at a corner with a small circle on the left wall and a large circle on the right wall, the inherent possibility of left–right spatial ordering of cues supports successful reorientation behavior. Nonscalar cues, on the other hand, tend to involve categorical representations (e.g., circle–diamond). The relations between stimuli in such pairs, although familiar, do not invoke an intuitive left–right orientation. That is, the order of circle–diamond versus diamond–circle is arbitrary and thus does not afford straightforward directional mappings (e.g., left–right or right–left) as navigational cues to location. In this way, the underlying manner in which scalar cues are represented (i.e., in terms of their underlying order) may be crucial to the success or failure on spatial reorientation tasks by young children.

Prior studies of reorientation (including Huttenlocher & Lourenco, 2007) have predominantly utilized symmetrical spatial layouts. It is important to note that for these layouts, the configuration of cues consists of two pairs of identically marked corners (e.g., see Figure 1c–d in the current study). In a symmetrical layout, children can only distinguish opposite corners of a space from the other two corners, leading to a probabilistic task in which optimal search results in only 50% accuracy. That is, even with perfect attention to and memory for relevant cues, optimal response only narrows the search from four to two possible hiding locations—leaving only a 50/50 chance of choosing the actual hiding location. Therefore, the reliability of these cues for identifying location is quite low. Cue reliability (i.e., the probability that a given cue predicts some outcome in the environment) has been shown to be an important factor for success on tasks

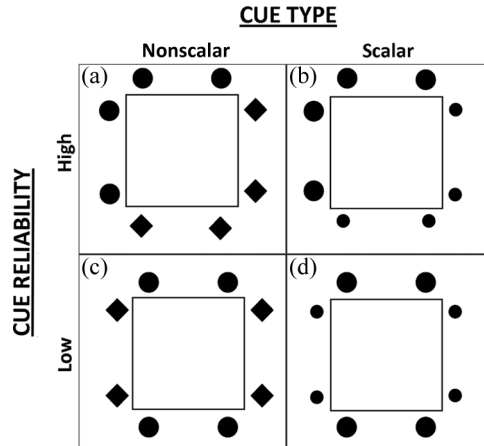


FIGURE 1 A schematic bird's-eye view of the stimulus configurations in Experiments 1 through 4 [a–d], respectively. Note that in Experiments 1 and 2 ([a] and [b]), each corner can be determined with 100% accuracy—Experiments 1 and 2 were thus considered to have high cue reliability. By contrast, in Experiments 3 and 4 ([c] and [d]), the symmetrical layout allows for rejection of only half of possible hiding locations: The true location and its diagonal opposite are identical; because of this 50/50 level of uncertainty, Experiments 3 and 4 were considered to have low cue reliability. In addition, note that nonscalar cues (circles and diamonds with identical surface area) were used in Experiments 1 and 3 ([a] and [c]); scalar cues (varying in relative circle size) were used in Experiments 2 and 4 ([b] and [d]).

involving a diverse range of methods, domains, and species (Cornell, 1979; Eriksen & Yeh, 1985; Giessing, Thiel, Rösler, & Fink, 2006; Jacobs, 2002; Maltz & Shinar, 2003; Morgan, DeAngelis, & Angelaki, 2008; Muller, Brenner, & Smeets, 2009; Pouget, Dayan, & Zemel, 2003; Riggio & Kirsner, 1997). Of particular interest, Miller and Shettleworth (2007) present an elegant model that reproduces animal behavior driven by learned associations between a goal and either spatial features or variations in environmental geometry (e.g., variations in wall length). An important feature of the model is that it allows for modulation of associative strength based on frequency of feature–reward pairing (i.e., the reliability with which a given spatial or surrounding geometric cue predicts reward). However, to our knowledge, the role of cue reliability has not been addressed explicitly in the context of navigational reorientation in humans (children or adults). Hence, greater reliability of a cue, which increases its predictive power, may be expected to improve children's reorientation performance.

If cue reliability improves reorientation performance because of increases in the cues' predictive power, it would suggest reorientation is part of a visuomotor system in which a range of perceptual inputs is linked flexibly to a range of motor responses (Wise & Murray, 2000). Increasing cue reliability may improve performance regardless of whether cues are scalar or nonscalar, and differences in the ease of processing scalar versus nonscalar cues may thus be observed only when cue reliability is low.

Current Study

In Experiments 1 and 2, we used an enclosure involving a configuration of feature cues with 100% cue reliability. In such a configuration, identical walls were adjacent rather than opposite

one another (Figure 1a–b). In this spatial layout, all four corners are distinguishable from one another. Thus, 100% success is possible in locating the correct hiding location (vs. 50% possible success in prior reorientation studies). In Experiment 1, cues were nonscalar (circles or diamonds); in Experiment 2, cues were scalar (varying in circle size). Experiment 1 allowed us to test whether increasing cue reliability is sufficient to overcome children’s previously reported inability to use nonscalar cues during spatial reorientation (Huttenlocher & Lourenco, 2007; Lourenco et al., 2009). Experiments 3 and 4 provided important baseline measures. These latter two experiments used a configuration of cues that followed the typical symmetrical design in previous studies (e.g., Huttenlocher & Lourenco; Lourenco et al.; see also Twyman & Newcombe, 2010, for review), allowing for only 50% success; that is, cues were only 50% reliable (Figure 1c–d). Stimuli in Experiments 3 and 4 were otherwise identical to those in Experiments 1 and 2. In this way, we were able to orthogonally examine the relative influences of cue reliability and of scalar versus nonscalar cues on reorientation behavior.

As was previously reported in Huttenlocher and Lourenco (2007), we expected that when cues were scalar, children would succeed (i.e., perform on average above chance—significantly greater than 50% correct) even with low cue reliability (Experiment 4). We expected that when cues were nonscalar (Experiment 3), children would fail (perform at chance—50% correct) with low cue reliability. Crucially, when cue reliability was high, we predicted that children would succeed (perform above chance—significantly greater than 25% correct) when relying on both scalar (Experiment 2) and nonscalar cues (Experiment 1). If the predicted results were obtained, it would demonstrate that both the reliability of cues and the inherent scalar nature of cues are important determinants of spatial reorientation performance. At a broader level, the result would support the notion that spatial navigation (at least in a reorientation context) is based on a broad network of processes responsible for establishing visuomotor associations more generally, rather than on a task-specific “geometry module” (Lee & Spelke, 2010).

It is important to note that at least one other study (Lew, Gibbons, Murphy, & Bremner, 2010) indirectly examined the influence of cue reliability on reorientation performance. In the first experiment by Lew et al., 18- to 36-month-old children were presented with a reorientation procedure similar to the one used in the present article. Half of the children were placed in a symmetrical rectangular room and were searched at the correct and diagonally opposite corners significantly above the 50% chance mark. The remaining children were presented with an irregular quadrilateral structure, where the relative lengths of the four walls were unique. Children did not search above chance (25%) in the irregular structure. This result seems at odds with the notion that increasing cue reliability to 100% increases successful search at the correct hiding location. However, the success rate in their study was 32%, and given that Lew et al. tested only 16 children, a simple power analysis ($power = .34$) suggests that Lew et al. may have tested too few subjects. Thus, in all our experiments, we tested 24 children; importantly, in Experiments 1 and 2 (in which cue reliability was made 100%), statistical power was appreciably higher (.79 and .93 in Experiments 1 and 2, respectively). In addition, the wall lengths in Lew et al. were 1.95 m, 1.86 m, 1.26 m, and 1.05 m, yielding a maximum ratio under 2:1 (1.95:1.05) and a minimum ratio of about 22:21 (1.95:1.86)—a ratio far more precise than that which 3-year-olds can distinguish (between 2:3 and 3:4), even when number and area are allowed to covary (Halberda & Feigenson, 2008). Indeed, even adults can distinguish ratios only up to around 10:9 (Halberda & Feigenson; Pica, Lemer, Izard, & Dehaene, 2004). Hence, in addition to lack of power, one reason for Lew et al.’s failure to find a positive influence of cue reliability on reorientation

performance may simply be that although cues were reliable, they were difficult to distinguish from one another. Thus, in the current study, the sizes of our scalar stimuli (Experiments 2 and 4) differed by a ratio of 3:1—a size difference that should easily be distinguishable for children at this age (Brannon, Lutz, & Cordes, 2006).

METHOD

Participants

Each experiment include separate samples of 24 children. Across all four experiments, 20 additional children were excluded because they became too fussy or there was an external cue (e.g., the parent stood in the same place or there was a bag left on the floor in view of the child) inadvertently present during the trials. All trials were videotaped and were subsequently reviewed in addition to experimenters' notes to assess which participants should be removed from further analyses. After removing these participants from the data set, each experiment included 24 children. The children in Experiments 1, 2, and 4 were aged 18 to 24 months old (Experiment 1, $M_{\text{age}} = 1;9$, $SD = 1.72$ months; Experiment 2, $M_{\text{age}} = 1;9$, $SD = 2.17$ months; Experiment 4, $M = 1;9$, $SD = 1.54$ months). The children in Experiment 3 were aged 24 to 30 months old ($M_{\text{age}} = 2;3$, $SD = 1.85$ months). Adults readily succeed in using beacon-like features in configurations akin to that used in Experiment 3 here (Ratliff & Newcombe, 2008a, 2008b). Thus, because we predicted children would be most likely to fail in Experiment 3, increasing children's average age in this experiment served as an even stronger test of our hypothesis.

Stimuli

The experiments took place inside a larger circular space (3.8 m across, 2.3 m high) with no identifying landmarks. The entire space was completely symmetrical, including the overhead lights, to reduce the chance that landmark cues could be used to mark a location in the room (except for the critical stimuli provided on the walls of the square space). The square experimental enclosure was placed in the center of the room. The enclosure was a white square-shaped box (open at the top; 99.1 cm \times 45.7 cm). Within this box, identical containers were located in each of the four corners to serve as potential hiding locations. Two black shapes were placed on each inner wall of the box (12.7 cm from the nearest corner) to serve as potential navigational cues (Figure 1). In Experiments 2 and 4, the shapes were small (radius = 6.35 cm) and large (radius = 11 cm) circles (note that small circles were thus one third of the surface area of large circles). In Experiments 1 and 3, the shapes were circles (radius = 11 cm) and diamonds (side length = 19.5 cm; note circles and diamonds were thus equated in terms of surface area).

Procedure

The experimenter tested children individually with a parent present. The experimenter instructed the parent to place the child inside the box. The experimenter stood outside of the box and pointed to each of the box's walls, drawing the child's attention to the black shapes. The experimenter then hid the toy in one of the containers while the parent, who also stood outside

the box, moved around to avoid serving as a landmark. After the toy was hidden, the parent stepped inside the box, picked up the child, covered his or her eyes, and rotated four to five times. The parent then stopped, uncovered the child's eyes, and placed him or her facing one of the walls, which was randomly selected and counterbalanced across children. The parent and experimenter stood outside the box in front of the same wall as the child. The child then searched for the hidden toy from inside the space.

Each child performed six trials; for a given child, the toy was hidden in the same corner across all trials. This procedure is common in reorientation studies, because changing the hiding corner confuses young children. The location of the hiding corner among the four possibilities was counterbalanced across children. Thus, the correct corner was equally distributed for a given experiment but remained constant for each child. Our dependent measure was the mean percentage of correct searches. In none of the four experiments did the proportion of correct searches significantly differ based on the hiding corner location (all $ps \geq .572$, two-tailed). Furthermore, we ran a group of 14 children in a control procedure where the four sides of the square were plain white. Children responded at chance levels (i.e., at 25% for each of the corners). We thus conclude that extraneous factors did not affect response levels.

RESULTS

Figure 2 shows responses for all four experiments. The white bar at the left for each experiment shows the average percentage of correct responses. In Experiments 1 and 2, each corner was

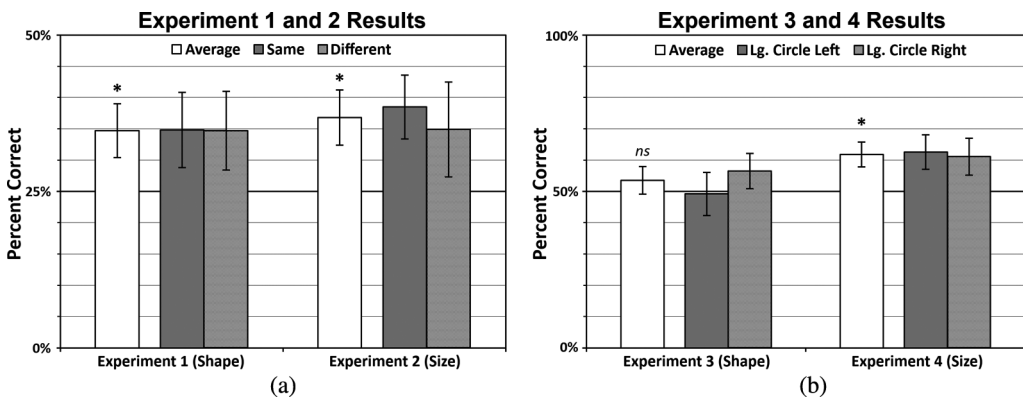


FIGURE 2 Results from all four experiments. Y-axes are the percentage of correct searches. Note that chance was 25% in Experiments 1 and 2 ([a]) and 50% in Experiments 3 and 4 ([b]). Error bars depict standard errors of the mean. Critical contrasts were conducted using the white bars (an asterisk indicates significant deviation from chance; $p < .05$). White bars are the average of the two grey bars. Note that not all participants saw the desired item hidden in the same corner. For Experiments 1 and 2, this allowed us to test whether performance depended on whether they saw the item hidden in a location specified by two identical stimuli (e.g., circle–circle) or the exact left–right configuration of two different stimuli (e.g., circle–diamond). The two grey bars in each case indicate that there was no significant difference in search performance in either experiment in a manner that depended on whether the hiding location was represented by same or different stimuli. In Experiments 3 and 4, we were able to use the same reasoning to test whether performance depended on a particular left–right configuration of stimuli (e.g., circle–diamond vs. diamond–circle in Experiment 3 or small–large vs. large–small in Experiment 4). The grey bars in each case indicate that no such dependency was found.

uniquely identifiable by the left–right relation between the shapes near the walls making up that corner. Hence, successful navigation was measured in terms of whether the child searched at above-chance level in the correct hiding corner (with chance performance corresponding to 25% of searches in that corner). In Experiment 1, using nonscalar cues, children searched in the correct corner 34.7% of the time on average, which was significantly above chance, $t(23) = 2.28$, $p = .032$ (two-tailed; Figure 2a, left, white bar). Searches did not significantly exceed chance at any of the incorrect corners (incorrect corners I_{1-3} refer to the three corners starting to the right of the correct corner and continuing in clockwise fashion; I_1 , $M = 18.8\%$, $SE = 3.6\%$, $t < 0$, $p = n/a$; I_2 , $M = 20.9\%$, $SE = 3.2\%$, $t < 0$, $p = n/a$; I_3 , $M = 25.7\%$, $SE = 3.4\%$, $t(23) = 0.21$, $p = .839$ [two-tailed]). In Experiment 2, using scalar cues, children searched in the correct corner 36.8% of the time on average, which was significantly above chance, $t(23) = 2.70$, $p = .013$ (two-tailed; Figure 2a, right, white bar). Searches again did not significantly exceed chance at any of the incorrect corners (I_1 , $M = 16.0\%$, $SE = 4.4\%$, $t < 0$, $p = n/a$; I_2 , $M = 25.7\%$, $SE = 3.7\%$, $t(23) = 0.19$, $p = .855$ [two-tailed]; I_3 , $M = 21.5\%$, $SE = 3.1\%$, $t < 0$, $p = n/a$). Thus, in a spatial layout that uniquely identifies each corner, children use both scalar and nonscalar cues to reorient in a square space.

One possible explanation for the pattern of response observed in Experiments 1 and 2 is that the hiding corner for half of the children involved two identical stimuli, so these children did not need to encode the left–right relation between stimuli. That is, for half of participants, the hiding location was specified by two identical stimuli—for example, two large or two small circles—whereas for the remaining half of participants, the correct location was specified by two different stimuli with a specific left–right relation (e.g., a circle on the left and a diamond on the right vs. the other way round; see Figure 1). If children succeeded in Experiments 1 and 2 primarily because they did not need to encode the left–right relation for a stimulus pair, then trials where the correct location involved a specific left–right combination of two different stimuli should be more difficult.

A between-groups contrast of the proportion of correct searches (comparing the two gray bars in Figure 2a) showed no difference for same-stimulus corners (same shape in Experiment 1; same size in Experiment 2) versus different-stimulus corners: Experiment 1, $t(22) = 0.01$, $p = .992$ (two-tailed); Experiment 2, $t(22) = 0.40$, $p = .690$ (two-tailed). Thus, our data cannot be explained solely by the fact that some participants did not need to encode left–right relations between stimuli to identify the hiding corner. Rather, it seems that cue reliability—regardless of same or different (left–right) configuration or even stimulus type (scalar or nonscalar)—is a general mechanism explaining children’s performance in Experiments 1 and 2.

In Experiments 3 and 4, we next examined whether reducing cue reliability from 100% to 50% (while using the same stimuli) would reduce reorientation performance. Diagonal corners were made indistinguishable from one another. Hence, successful navigation was measured in terms of whether the child correctly searched *either* in the correct hiding corner *or* its diagonal counterpart (with chance performance corresponding to 50% of searches in the correct and diagonal corners combined). In Experiment 3, using nonscalar cues, children searched in either the correct or the diagonal corner 53.5% of the time on average, which did not significantly differ from chance, $t(23) = 0.79$, $p = .435$ (two-tailed; see Figure 2b, left, white bar). In Experiment 4, using scalar cues, children searched in either the correct or the diagonal corner 61.8% of the time on average, which was significantly above chance, $t(23) = 2.99$, $p = .007$ (two-tailed; see Figure 2b, right, white bar). Thus, when cue reliability was low, children’s performance did depend on stimulus type (i.e., scalar vs. nonscalar).

In addition to the control experiment noted in the “Procedures” section, it is important to know whether children searched more or less equally often at the actual hiding location and its diagonal opposite (which are identical in terms of visual cues). Thus, for Experiments 3 and 4, we asked, of the searches made at either of the two correct corners (the sum of searches made at the actual hiding location and its diagonal counterpart), what percentage of these searches was at the actual hiding location. We next asked whether this percentage differed from 50%. That is, when searching at either the actual or diagonally opposite location, if significantly more than half of these searches was to the actual hiding location, this would indicate the presence of some extraneous factor beyond the cues themselves that helped children navigate to the exact hiding location. In Experiment 3, 54.5% ($SE = 5.3\%$) of correct searches were to the actual hiding location, which was not significantly greater than 50%, $t(23) = 0.85$, $p = .403$ (two-tailed). In Experiment 4, 51.8% ($SE = 3.8\%$) of correct searches were to the actual hiding location, which was again not significantly greater than 50%, $t(23) = 0.47$, $p = .643$ (two-tailed). We thus conclude that children were not influenced by extraneous factors beyond the visual cues themselves.

In Experiments 3 and 4, the correct hiding location was always specified by a left–right combination. In Experiment 3, children either saw the object hidden in a circle–left/diamond–right configuration, or in a diamond–left/circle–right configuration. In Experiment 4, children either saw the object hidden in a small–left/large–right configuration, or they saw the object hidden in a large–left/small–right configuration. To ensure that one arrangement was not more difficult than the other, we compared performance as a function of left–right stimulus configuration in each experiment (the two gray bars in Figure 2b). A between-groups contrast of the proportion of correct location searches showed no difference for left–right/right–left combinations: Experiment 3, $t(22) = 0.19$, $p = .855$ (two-tailed); Experiment 4, $t(22) = -0.47$, $p = .644$ (two-tailed). Interestingly, the results from Experiment 4 indicate that performance was not better when left–right orientation of the correct hiding location was small–big versus big–small—a finding somewhat in contrast to the small–big bias found with newborn chicks (Rugani et al., 2010, 2011). It may be that in a navigation task such as this, violations of a left–right rule for small–large scalar stimuli are just as salient to young children as stimuli in keeping with the rule. Alternatively, it may be that in human children, there is simply a bias to process scalar stimuli as having some form of spatial order; however, the exact direction of that order may not be specified until later in development, perhaps by cultural factors such as reading direction (e.g., Shaki, Fischer, & Petrusic, 2009).

DISCUSSION

Recent findings indicate that young children (18–30 months) may succeed in reorienting when using scalar cues to navigate but fail when cues are nonscalar (Huttenlocher & Lourenco, 2007; Lourenco et al., 2009). This finding, however, does not address whether variability in the relation between a given cue and an outcome in the environment (cue reliability) is predictive of how well children will form an association between a given cue and a particular response (navigate to the correct hiding corner). In the current study, we found evidence that high cue reliability is an important factor for determining the difficulty of reorientation: increasing cue reliability allows children to use both scalar and nonscalar cues for successful

reorientation—something children at this age were previously not thought capable of. Finally, consistent with prior work, we find that scalar cues (presumably because of their inherent order) can lead to competent performance even with weak cue reliability. As will be discussed, these results provide evidence that children's cue-driven spatial-reorientation ability is part of a broader system of flexible visuomotor behavior.

Nearly all models of learning assume that the probability with which a given stimulus predicts an outcome is a key determinant of the strength of the association linking the stimulus and a response (e.g., Jacobs, 2002; Muller et al., 2009; Pouget et al., 2003). Indeed, Hebbian learning rests on the computational notion that probability of co-occurrence is in fact *the* primary means by which stimulus–response associations arise (e.g., Gerstner & Kistler, 2002; Munakata & Pfaffly, 2004). One reason that nearly all models of memory place heavy emphasis on the variation of stimulus–response reliability is that the probability of a stimulus being paired with a desired outcome has been shown to drive behavior in a wide range of contexts (e.g., Cornell, 1979; Erikson & Yeh, 1985; Maltz & Shinar, 2003; Morgan et al., 2008; Riggio & Kirsner, 1997). Consistent with this notion, when presented with high cue reliability in the current study, children's performance was no longer dependent on the nature of stimulus representation (scalar or not): Children could succeed even with nonscalar cues—something that they had previously been thought incapable of (Huttenlocher & Lourenco, 2007; Lourenco et al., 2009). Given that sensitivity to cue reliability is such a pervasive property of flexible visuomotor systems in general (as discussed earlier), it seems that children's reorientation behavior is best understood as part of a broader set of mechanisms responsible for linking visual perception with motor behavior in general (Wise & Murray, 2000), rather than as an isolated cognitive module.

One implication of this view is that it may be fruitful to examine how reorientation behavior depends on the interaction between multiple cognitive and neural mechanisms. For instance, work in both cognitive and behavioral neuroscience is consistent with the view that visual maps that are important for egocentric guidance of hand movements, eye movements, and head orientation occupy both separate and overlapping sections of the intraparietal cortex in humans and monkeys (Culham & Valyear, 2006; Grefkes & Fink, 2005; Patel et al., 2010; Silver & Kastner, 2009; Trillenberg et al., 2007). As a more concrete example, children as young as 6 months of age use object size as a cue for selecting between types of manual behavior: Smaller objects elicit grasping behavior, whereas large objects elicit exploratory behavior (contacting and gliding one's hand across a surface; see Braddick & Atkinson, 2007, for a review). Perhaps, then, sensitivity to certain types of cues (e.g., relative size) that develop to guide other types of visuomotor behavior at an early age (e.g., determining grasp type in 6-month-olds) may be co-opted for use later in development for other, nonobviously related behaviors (e.g., the strong sensitivity to scalar cues in reorientation behavior in 18- to 30-month-olds). Though admittedly speculative, it is worth noting that this idea is not without precedent: Considerable evidence has accrued in other domains, such as reading and number representation, suggesting that certain complex abilities co-opt and perhaps even reorganize more evolutionarily primitive and developmentally basic neural structures and behavioral patterns (Dehaene & Cohen, 2007). In sum, we suggest that a complete, mechanistic understanding of the development of spatial reorientation will draw on properties both common and distinct across different subsystems underlying various forms of visually guided action.

As noted, even in the face of low cue reliability, children were able to use scalar cues to guide successful search behavior in Experiment 4, but not nonscalar cues in Experiment 3. How might

this differential influence of cue representation be reconciled with a broader visuomotor account of young children's reorientation behavior? Recently, considerable attention has been paid to the view that agreement between specific stimulus representations and action outcomes can facilitate relevant forms of motor performance (Gottlieb, 2007; Gottlieb, Balan, Oristaglio, & Schneider, 2009). For example, representation of scalar magnitudes has been shown to influence excitability of hand muscles (Sato, Cattaneo, Rizzolatti, & Gallese, 2007), grip aperture (Andres, Davare, Pesenti, Olivier, & Seron, 2004), hand-reaching trajectories (Song & Nakayama, 2008), and even to influence selection of different types of grasping motions (e.g., a power vs. a precision grip; Lindemann, Abolafia, Girardi, & Bekkering, 2007). Furthermore, there is mounting evidence that both ordinal and scalar representation are strongly related to egocentric conceptions of space (Buetti & Walsh, 2009; Gevers et al., 2003; Hubbard et al., 2005; Previtali et al., 2010; Rugani et al., 2010, 2011). The current study shows that the inherent spatial ordering of scalar representations aids performance in a spatial reorientation task that relies on ordered left–right associations between stimuli. Specifically, mapping of specific left–right visual features onto a viewer-centric sense of left and right is facilitated when features themselves are represented in an ordered manner. This in turn aids the mapping of these relations onto the desired motor behavior (navigate to the correct hiding corner to retrieve the toy). The strength of this effect is such that it can even overcome situations involving relatively low cue reliability (Experiment 4).

It is also worth noting that children at this age may be able to use a single, highly distinct cue under certain conditions to reorient themselves as a kind of “beacon” (Lee & Spelke, 2010). One possible interpretation is that beacons improve cue reliability to 100%; hence, cue reliability might provide a more general explanation that unifies work using beacons into a more general framework centered on the flexible linking of various stimuli and responses. On a related note, previous studies have shown mixed results with respect to children's ability to use landmarks or beacons to reorient in small (e.g., $\leq 4\text{ ft} \times 6\text{ ft}$) enclosures (Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001; Lee & Spelke). It is worth noting that these studies examining the use of beacons in small enclosures tend to color a single wall blue in an otherwise all-white enclosure. In the current Experiments 1 and 2, we used the left–right spatial combination of two items to identify each corner. The fact that each corner was thus marked by some cue might have biased children to attend more readily to the potential navigational usefulness of these cues. Albeit speculative, from this, one might predict that if each of the four walls were given a different, highly distinctive color, then even in a small enclosure, children aged 18 to 24 months old might be more likely to hit upon the potential usefulness of this variation in coloration and thus would show a pattern of search results more akin to that found in Experiments 1 and 2 here.

In conclusion, we report on two factors that are important for determining reorientation in young children: cue reliability and cue representation. We suggest that both factors can be understood within existing frameworks for explaining visually guided motor behavior more generally, namely that cue reliability improves performance in most systems that provide for the flexible linking between stimuli and responses (for reorientation behavior; Ratliff & Newcombe, 2008b). Furthermore, the represented properties of some stimuli can be directly related to a specific response, so the afforded link between stimulus and response in such cases is especially robust, even in the face of low cue reliability. In this way, we believe that children's reorientation behavior can be understood in terms of more general visuomotor system properties, without reference to task- or domain-specific developmental “modules” (e.g., Lee & Spelke, 2010).

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