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The relations among navigation, object analysis, and magnitude perception in children:
Evidence for a network of Euclidean geometry

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Abstract

What is the relation between navigation and object analysis? Although researchers agree that such systems are, to some extent, dissociable, open questions remain about the potential interactions between them. Using an individual differences approach with young children (4-year-olds; $N = 90$), we examined the novel proposal that navigation and object analysis interact indirectly by way of magnitude perception. A system for magnitude perception may be ideally suited to support such interactions because it is present from early in development and is capable of discriminating geometric properties on the basis of spatial extent. Across two experiments, we tested for relations between children's ability to reorient within an environment, analyze the geometric properties of object forms, and discriminate area. We found that area precision was correlated with both reorientation ability and geometric form analysis, though reorientation and form analysis did not correlate with one another. Importantly, we also found that the precision of children's area discrimination supported an indirect link between their reorientation ability in a physical environment and visual analysis of object forms. Together, these results suggest a network for representing Euclidean geometry that includes both direct and indirect relations among navigation, object analysis, and magnitude perception. The potential role of magnitude perception within such a network is discussed.

Keywords: navigation; categorization; modularity; magnitude perception; geometry

Introduction

The primitives of Euclidean geometry provide humans (and other animals) with the basic structure for organizing the physical world. Perceptual primitives, such as points and lines, give way to a variety of geometric properties, such as length, angle, and distance. These geometric properties are crucial for physically navigating the environment and for classifying objects. There is general agreement that the use of Euclidean geometry for both navigation and object classification is universal. However, there is ongoing debate about the relations between these two systems, including the types of geometric properties relevant to navigable environments and objects, as well as the extent of communication between these systems.

There are researchers who argue that because navigation and object classification are supported by neurally distinct brain regions, they form cognitively independent systems (Dillon, Huang, & Spelke, 2013; Lee, Sovrano, & Spelke, 2012; Spelke, Lee, & Izard, 2010). According to this view, a navigation system, which involves determining one's location and reorienting within a 3D environment, and an object classification system, which involves analyzing form to determine object identity or category, are encapsulated, such that the geometric information available to one system is not available to the other (Fodor, 1983; Spelke et al., 2010). Advocates of this perspective argue that children, and some nonhuman animals, accomplish navigation by relying exclusively on the geometric properties of distance and direction, whereas object classification is accomplished using geometric properties such as length and angle, or non-geometric features such as color and pattern. Direct evidence for this proposal comes from Lee et al. (2012) who showed that, within fragmented spaces, children relied on the distances between walls to reorient, not the lengths of the walls, or the angular sizes of the corners (see also, Hu, Zhang, Wu, & Shao, 2015; Hupbach & Nadel, 2005). Further support comes from research showing that infants discriminate objects using properties such as length and angle (Baillargeon & Graber, 1987; Bomba & Siqueland, 1983; Lourenco & Huttenlocher, 2008), and older children have difficulty using the directional properties of left and right in object classification tasks (Gregory, Landau, & McCloskey, 2011). Indeed, across cultures and differing levels of geometry education, children's performance on such tasks is best on trials that require perception of length and angle compared to distance and direction (Dehaene, Izard, Pica, & Spelke, 2006; Izard, Pica, Spelke, & Dehaene, 2011; Izard & Spelke, 2009). Finally, classic work in neuroscience has emphasized the distinction between navigation and object classification by highlighting the domain-specificity of the dorsal stream for location information (e.g., distance and direction) and the ventral stream for form information (e.g., length and angle; Goodale & Milner, 1992; Milner & Goodale, 1993).

Using an individual differences approach, Dillon et al. (2013) provided evidence that systems of navigation and object classification relied on different geometric properties. In particular, they found that, among 4.5-year-olds, performance on a reorientation task with rectangular enclosures did not correlate with performance on a form analysis task that required selection of a non-matching (i.e., odd-one-out) geometric property for a set of object forms. Moreover, the authors found that children's scores on reorientation and form analysis tasks were differentially related to their scores on mapping tasks that required the use of distance or angle cues, respectively. In particular, children's reorientation

performance was related to their ability to use distance, but not angle, on the mapping task, whereas their performance on the form analysis task was related to their ability to use angle, but not distance, on the mapping task. These findings provide further support for the independence of navigation and object systems, specifically as it relates to the geometric properties accessed by each system.

It has been suggested that navigation and object systems only come to interact once children are capable of describing spatial information symbolically. From this perspective, experience with spatial-relational language and/or maps comes to circumvent encapsulation by recoding geometric information into a common format, thereby allowing geometric properties to be used flexibly for either navigation or object classification (Spelke et al., 2010). Previous work on spatial language suggests that such flexibility may be possible by 5-6 years of age when children come to understand words such as left and right (Hermer-Vazquez, Moffet, & Munkholm, 2001; Shusterman, Lee, & Spelke, 2011). Other work suggests that children's proficiency in using maps predicts their ability to flexibly use geometric cues for navigation or objects (Dillon & Spelke, 2018). In this view, it is not until 10 years of age that children have sufficient symbolic experience to allow for systems of navigation and objects to share geometric information.

However, findings from other studies suggest that, with little or no symbolic experience, children, and even nonhuman animals, use a variety of geometric (and non-geometric) cues for both navigation and object analysis (Cheng, Huttenlocher, & Newcombe, 2013; Cheng & Newcombe, 2005; Twyman, Newcombe, & Gould, 2013). For example, young children and nonhuman animals (e.g., mice and fish) have been found to reorient within a square environment using 2D wall patterns when these patterns reliably distinguish the corners (Huttenlocher & Lourenco, 2007; Lee, Vallortigara, Ruga, & Sovrano, 2012; Lyons, Huttenlocher, & Ratliff, 2014; Twyman & Newcombe, 2010; Twyman, Newcombe, & Gould, 2009). Moreover, children are capable of using wall length to reorient in a fragmented space when the positions of the walls do not generate ambiguous global shape information (Yousif & Lourenco, 2017). Similarly, infants have been shown to use direction (i.e., left and right) and distance cues to categorize objects in visual attention paradigms (Gava, Valenza, & Turati, 2009; Newcombe, Huttenlocher, & Learmonth, 1999; Quinn, 2012). And although 4-year-olds have more difficulty using distance and direction cues to distinguish object forms than they do length and angle, they are nevertheless able to use all of these cues at above chance levels (Dehaene et al., 2006; Izard & Spelke, 2009). Taken together, these data would seem to suggest a network for representing Euclidean geometry, with less encapsulation than argued by the opposing perspective. Indeed, neuropsychological studies with patients and neuroimaging studies with healthy individuals indicate that the classic division of dorsal and ventral pathways downplays the interconnections between them (Freud, Plaut, & Behrmann, 2016; Gilbert & Li, 2013; Milner & Goodale, 2008). Contemporary views emphasize that both dorsal and ventral pathways process similar types of information (Freud, Culham, Plaut, & Behrmann, 2017; Hong, Yamins, Majaj, & DiCarlo, 2016; Kravitz, Saleem, Baker, & Mishkin, 2011), though the relevant content may be used in functionally specific ways (Dilks, Julian, Kubilius, Spelke, & Kanwisher, 2011; Dillon, Persichetti, Spelke, & Dilks, 2017). Similarly, the dissociations reported by Dillon et al. (2013) may demonstrate the functional specificity of Euclidean geometric properties

when used for navigation or object classification, but not the encapsulation of these systems. There may be broader connections—direct and indirect—that could result in the use of the same Euclidean properties for navigation and objects. Yet how this flexibility is achieved and the degree to which navigation and object systems interact remain unclear.

Present Study

The present study attempted to reconcile extant findings by testing a proposal heretofore not considered in the literature. In particular, we asked about the potential role of magnitude perception within a network for representing Euclidean geometry. A system for processing magnitude information may be ideally suited to support interactions between navigation and object analysis because many geometric properties are distinguished by magnitude properties such as spatial extent. For instance, to be used for navigation, distances must be compared on the basis of their extent from the navigator (e.g., close or far). Likewise, cues such as length and angle are compared by the degree of extent between their endpoints (e.g., short or long) or adjoining segments (e.g., narrow or wide). Moreover, discrimination of distance (Dillon et al., 2013), length (DeWind & Brannon, 2012), and angle (Chen & Levi, 1996; Heeley & Buchanan-Smith, 1996) all abide by Weber's law, suggesting a common perceptual mechanism, though perception of these cues can also be affected by contextual factors (Dillon, Duyck, Dehaene, Amalric, & Izard, 2019; Huttenlocher, Hedges, Corrigan, & Crawford, 2004; Muller-Lyer, 1889; Yousif & Lourenco, 2017). Importantly, a system of magnitude perception has been found to be operational from early in development (Brannon, Lutz, & Cordes, 2006; Lourenco & Longo, 2010), a key feature if magnitude perception is relevant to a network of Euclidean geometry prior to extensive symbolic experience. Indeed, if magnitude perception is relevant to both navigation and object analysis, then it would explain why there are cases in which the same geometric properties are used for navigation and objects (Cheng & Newcombe, 2005), even though these two systems dissociate by function.

Preliminary evidence for this hypothesis comes from Bonny and Lourenco (2015) who found that children's understanding of the geometric properties of objects, as assessed by the form analysis task used by Dillon et al. (2013), correlated with an ability to discriminate the areas of 2D shapes. Moreover, it has been shown that young children are able to reorient in a square enclosure when 2D magnitude information placed on the walls (e.g., small dots on one set of walls and large dots on another set) distinguishes adjacent corners (Huttenlocher & Lourenco, 2007; Lee, Winkler-Rhoades, & Spelke, 2012; Lourenco, Addy, & Huttenlocher, 2009; Lyons et al., 2014). Yet it remains unknown whether individual differences in reorientation ability also correlate with the precision of one's magnitude perception. Moreover, if magnitude perception supports interactions between systems of navigation and object analysis, then magnitude perception may serve as an indirect mediator between the two systems. And importantly, if magnitude perception supports these relations independently of symbolic experience, then these relations should be found at an age when symbolic experience is minimal.

Experiment 1

In Experiment 1, we examined the relation between children's navigation ability and the precision of their magnitude perception. Children were 4-year-olds, an age when children

have had little experience with maps (Dillon & Spelke, 2018; Hermer-Vazquez et al., 2001; Liben & Downs, 1989; Uttal & Sheehan, 2014). Following previous research, we assessed the relation between navigation ability and magnitude perception by comparing inter-individual variability across two tasks. Navigation ability was assessed with a reorientation task in which children attempted to localize a target within a bounded space, and magnitude perception was assessed with an area discrimination task in which children indicated the larger of two 2D shapes. It was previously found that 4- to 6-year-olds' performance on an object form analysis task correlated with their ability to discriminate area (Bonny & Lourenco, 2015), but it is unknown whether children's navigation ability is also correlated with the precision of their magnitude perception. If the representation of magnitude is relevant to a navigation system, then children's reorientation performance should correlate with area discrimination.

Because other research has found that spatial language affects children's reorientation ability (Hermer-Vazquez et al., 2001; Shusterman et al., 2011), we included the Test of Relational Concepts (TRC; Edmonston & Thane, 1999). The TRC measures children's comprehension of relational language, particularly spatial vocabulary. If a correlation between navigation and magnitude perception held when controlling for spatial vocabulary, it would help to ensure the specificity of the relation between the two abilities of interest.

Method

Participants

Thirty 4-year-olds ($M = 48.84$ months, $range = 43.8$ -52.93 months; 17 girls) participated in this experiment. Children were recruited from a metropolitan community and tested in a university laboratory. Informed consent was obtained from children's caregivers and each child received a small gift for participating. Experimental procedures were approved by the local Institutional Review Board (IRB).

An a priori power analysis was conducted in accordance with population effect sizes suggesting moderate effects (Bonny & Lourenco, 2015: $r = 0.49$). This analysis indicated adequate power ($1 - \beta > 0.85$) within our sample to detect a correlation between reorientation and area discrimination.

Tasks and procedure

Children were tested individually by a single experimenter, completing three tasks in a fixed order (reorientation, area discrimination, and TRC). The first task was a reorientation task in which children were directed to find a toy in one of four corners of a rectangular enclosure following disorientation (Hermer & Spelke, 1994). Each space was made up of four equal-lengthened walls (76 cm long, 46 cm high) arranged in a rectangular array (see Figure 1A). We used fragmented, rather than enclosed, spaces to isolate the geometric properties of distance and direction. Unlike an enclosed rectangular space, the walls here were equal in length, removing the availability of length information (Lee et al., 2012). To maximize individual differences, children were tested in three conditions (counterbalanced

order) that varied in aspect ratio (i.e., larger distance divided by smaller distance: 2.00, 1.50, and 1.33). There were four identical containers, each placed at the presumed corner of the completed rectangular space, and one of which served as the hiding location (location counterbalanced across children). In each condition, the testing space was positioned within a larger circular room (diameter = 3.35 m, height = 2.6 m) with no visible markings.

On each trial of the reorientation task, the experimenter hid a toy at the target container. The experimenter then disoriented the child by spinning them around for approximately 10 seconds (~4-6 rotations) while the child covered their eyes. Following this procedure, children were placed in front of one of the walls (randomized order across trials) and instructed to search one of the containers for the hidden toy. If they searched at the incorrect corner, the experimenter revealed the toy's location. Each child received three blocks of four trials (i.e., 4 trials per ratio, 12 trials total). There were short breaks between blocks in which children left the room. During this time, the walls were changed to reflect the new condition.

The second task children completed was an area discrimination task administered on a laptop computer (see Figure 1B). Following Bonny and Lourenco (2015), on each trial, children were presented with pairs of figures, resembling puzzle pieces, and asked to judge which of the two was larger in area ($M_{area} = 28.9 \text{ cm}^2$, range: 21.4-52.5 cm^2). As in the reorientation task, we included different ratios (2.00, 1.50, 1.25, 1.17, and 1.11; larger value divided by smaller value) to maximize inter-individual variability. Pairs of figures were always presented simultaneously below Sesame Street characters (Bert and Ernie). Children were told to judge which figure was larger in area using the prompt "Who has more paint?" Figures remained onscreen until children responded by pointing to their answer. Children received four practice trials with a large ratio (3.00) and were given corrective feedback to ensure that they understood the task instructions. There were 40 test trials (8 trials per ratio; randomized order) with no corrective feedback.

The third task was the TRC (Edmonston & Thane, 1999), a standardized vocabulary measure of relational concepts. On each trial, children were presented with a page containing 3-5 different pictures and directed to select the picture that corresponded to the verbal concept (e.g., "Point to the butterfly that is *under* the table."). The TRC includes trials that assess canonical spatial language (e.g., "*under*") and spatial-relational concepts (e.g., "the *last* boy in line", "what happened *first*", and "the *smallest* pencil"). Children completed 56 trials following the standardized protocol. Scores are age standardized.

All children were tested by the same experimenter who was naïve to the hypotheses of the study.

A

B

C

Figure 1. Illustrations of the tasks used in Experiments 1 and 2. (A) A schematic of the three fragmented spaces used in the reorientation task. A container, which served as a potential hiding location, was placed at each 'corner' (red circles). Internal gray values indicate the conditions as defined by the ratio of the distances. External blue values (dotted lines) represent the length of each enclosure (116 cm width in all conditions). (B) Example trials from the area discrimination task. Children were required to answer which character had

more paint. (C) Example trials from the form analysis task in which children were required to select the image that did not belong with the others. On each trial, one of the images did not match the geometric property depicted in the others.

Results and Discussion

Preliminary analyses

Internal consistency was analyzed for reorientation and area discrimination tasks using split-half correlations (Spearman-Brown formula). Both tasks yielded acceptable reliability (reorientation task: $r = .62$; area discrimination task: $r = .68$). Moreover, reported reliability is high for the TRC ($r = .94$, test-retest; Edmonston & Thane, 1999). Children's performance was normally distributed on each task, with no task showing skew in the distribution of scores ($+/- 0.6$), nor kurtosis ($+/- 1.1$). No outliers were identified on any task using either univariate ($2.5 \times SD$ criterion) or multivariate (Cook's distances < 0.46) detection methods.

For each task, we examined whether children's performance varied by age or gender. Correlation analyses revealed no significant effects between age and accuracy on any task ($ps > .079$). Separate independent samples t-tests with gender as the between-subjects factor revealed no differences between boys and girls on any task ($ps > .433$).

Performance on the reorientation task

Children's accuracy on the reorientation task was assessed as searches to the target location (i.e., where the toy was hidden) or the location diagonally opposite the target (i.e., the geometric equivalent). See Table 1 for descriptive statistics. A 3-level repeated-measures analysis of variance (ANOVA), with condition (aspect ratio: 2.00, 1.50, 1.33) as the within-subjects factor revealed no significant effect of ratio ($p = .614$, $\eta_p^2 = 0.02$). Comparisons to chance (.50) revealed that performance was significantly above chance for all three ratios, $ts(29) > 3.16$, $ps < .005$, $ds > 0.58$ (see Figure 2A), demonstrating that children were capable of reorienting by distance and direction regardless of the aspect ratio of the space, consistent with previous research (Dillon et al., 2013; Learmonth, Nadel, & Newcombe, 2002). Moreover, children's searches were distributed evenly between the target locations and their geometric equivalents in all conditions ($ps > .229$), confirming disorientation.

Performance on the area discrimination task

Children's accuracy on the area discrimination task was assessed as the proportion of correct responses to total items. See Table 1 for descriptive statistics. A 5-level repeated-measures ANOVA, with ratio (2.00, 1.50, 1.25, 1.17, 1.11) as the within-subjects factor, yielded a significant effect of ratio, $F(4, 116) = 30.28$, $p < .001$, $\eta_p^2 = 0.51$ (see Figure 2B), and comparisons to chance (.50) revealed that performance was significantly above chance at all ratios, $ts(29) > 2.96$, $ps < .006$, $ds > 0.54$ (see Supplemental Table 1 for post-hoc comparisons), as found previously (Bonny & Lourenco, 2015; Odic, Libertus, Feigenson, & Halberda, 2013).

Is there a relation between reorientation and area discrimination?

To address this question, we ran a correlation analysis on children's reorientation and area discrimination scores. The analysis revealed a positive correlation, $r(28) = .42$, 95% CI [.07, .68], $p = .022$ (Figure 2C), such that children who performed better on the reorientation task also had higher scores on the area discrimination task (see Supplemental Table 2 for all correlations). Moreover, the relation between reorientation and area discrimination remained statistically significant when controlling for TRC scores, $r(27) = .45$, 95% CI [.10, .70], $p = .015$. Finally, although age did not correlate with either the reorientation or area discrimination task ($r_s < .33$, $p_s > .079$), we nevertheless also controlled for age in these analyses. The correlation between reorientation and area discrimination remained statistically significant when controlling for both age and TRC scores, $r(26) = .39$, 95% CI [.04, .66], $p = .033$.

In summary, children who were better at using distance/direction for reorientation also had more precise representations of magnitude, an effect that held when controlling for children's spatial language and chronological age. Thus, there was a specific relation between tasks that depended on the distance/direction within a 3D space and the area of 2D shapes, suggesting a link between a system of navigation and magnitude perception.

Table 1. Descriptive statistics of children's performance on each task in Experiments 1 and 2. Means (and SDs) on reorientation, area discrimination, and form analysis tasks are proportion correct. Mean (and SD) on the TRC are standardized ($M = 50$, $SD = 10$).

Experiment	Task	Condition	Mean	SD
Experiment 1				
	Reorientation	1.33	.65	.26
		1.50	.67	.29
		2.00	.71	.29
	Area Discrimination	1.11	.62	.22
		1.17	.61	.18
		1.25	.80	.20
		1.50	.83	.17
		2.00	.88	.17
	TRC		58.63	8.67
Experiment 2				
	Reorientation	1.33	.65	.31
		1.50	.70	.33
		2.00	.70	.31
	Area Discrimination	1.11	.57	.21
		1.17	.62	.18
		1.25	.69	.22
		1.50	.78	.21
		2.00	.83	.21
	Form Analysis		.37	.17

Figure 2. Children's performance on reorientation and area discrimination tasks in Experiment 1. (A) Proportion correct at each ratio of the reorientation task (dotted line indicates chance performance). (B) Proportion correct at each ratio of the area discrimination task (dotted line indicates chance performance). (C) Zero-order correlation between performance (proportion correct) on reorientation and area discrimination tasks.

Experiment 2

In Experiment 2, we tested the hypothesis that systems of navigation and object classification are indirectly related via magnitude perception. In the previous experiment, we found a correlation between children's reorientation ability and area discrimination. Bonny and Lourenco (2015) found a correlation between children's performance on area discrimination and the form analysis task, in which children identify object forms on the basis of different geometric properties. Here, we examined both types of correlations in 4-year-olds in an effort to replicate the previous findings for this age group. Moreover, the current experiment served as an important test of the lack of an association between children's reorientation and form analysis abilities, reported by Dillon et al. (2013). We sought to replicate this finding, as well as to test the possibility that magnitude perception might serve as a conduit between systems of navigation and object classification. Importantly, if magnitude perception is part of a larger network for representing Euclidean geometry, then even if navigation and object classification are not directly related, magnitude perception can still serve to support an *indirect* relation between the two (Hayes, 2009; Kenny, Kashy, & Bolger, 1998; Preacher & Hayes, 2008).

Although classic measures of indirect effects, such as the causal steps approach of Baron and Kenny (1986), stipulate a direct effect as a prerequisite for mediation analysis, an extensive literature has identified drawbacks with this approach, including low statistical power (Fritz & MacKinnon, 2007; MacKinnon, Lockwood, Hoffman, West, & Sheets, 2002). Instead, statisticians now advocate that researchers test for indirect effects on the basis of a priori predictions, rather than the existence of direct effects (Hayes, 2009; Kenny et al., 1998). To this end, we tested whether magnitude perception supports an interaction between navigation and object classification using mediation-by-design (Fairchild & McDaniel, 2017), given our a priori prediction of a potential role for magnitude perception in the relation between navigation and object classification.

As our measures of navigation ability and magnitude perception, we used the same reorientation and area discrimination tasks from Experiment 1. And as our measure of object classification, we used the form analysis task used in previous studies (Bonny & Lourenco, 2015; Dillon et al., 2013; Izard & Spelke, 2009). This task assesses children's understanding of geometric properties with 2D object forms. Across trials, children are assessed on their understanding of a variety of Euclidean concepts including proportional length, angle size, global shape, parallelism, symmetry, and alignment (see Figure 1C). The TRC was not included in this experiment because it was not related to either task in Experiment 1 and because of concerns regarding the length of the testing session.

Method

Participants

Sixty 4-year-olds ($M = 50.38$ months, range = 43.20 – 59.11 months; 31 girls) participated in this experiment. An additional eight children were tested but did not complete the study. Children were recruited from a metropolitan community and tested in a university laboratory. Informed consent was obtained by children's caregivers and each child received a small gift for participating. Experimental procedures were approved by the local IRB.

An a priori power analysis specifically for tests of indirect effects (Schoemann, Boulton, & Short, 2017) was conducted using Monte Carlo simulations and known correlation effect sizes (Experiment 1: $r = .42$; Bonny and Lourenco, 2015: $r = .49$; Dillon, Huang, and Spelke, 2013: $r = .03$). This analysis indicated adequate power ($1 - \beta > 0.85$) within our sample to detect a mediation effect.

Tasks and procedure

Children were tested individually by a single experimenter. All children completed three tasks, administered in a counterbalanced order. We counterbalanced the task order to ensure that effects could not be explained by procedural variables. Two tasks were repeated from Experiment 1: reorientation and area discrimination (see Figure 1A-B). Procedures for these tasks were identical to those of Experiment 1. The third task was the form analysis task frequently used to measure geometric understanding of different properties within object forms (see Figure 1C; Bonny & Lourenco, 2015; Dehaene et al., 2006; Dillon et al., 2013; Izard et al., 2011). On each trial, children were presented with six images, five of which shared a given geometric property (e.g., square) that the sixth image did not (e.g., rectangle). Children were instructed to select the one that violated the particular property (i.e., "Which picture is different and does not belong with the rest?"). Children were given two practice trials (one in which the odd-one-out differed in color; another in which it differed in orientation) with corrective feedback. No feedback was provided on the test trials. Children were given a total of 35 trials (2 practice and 33 test trials) on a laptop computer. The number of items was determined using an item analysis from the dataset of Bonny and Lourenco (2015), such that the lowest performing items

were removed from the current task in order to minimize guessing and to reduce floor effects.

As in Experiment 1, all three tasks were administered by the same experimenter who was naïve to the hypotheses of the study.

Results

Preliminary analyses

As in the previous experiment, we first conducted analyses of reliability and normality for each task. Reliability was assessed in terms of internal consistency using split-half correlations (Spearman-Brown formula). These analyses revealed reliabilities within an acceptable range for each task (reorientation task: $r = .64$; area discrimination task: $r = .61$; form analysis task: $r = .55$). Children's performance was normally distributed on all tasks, with no task showing skew in the distribution of scores ($+/- 0.6$) nor kurtosis ($+/- 1.2$). No outliers were identified on any task using either univariate ($2.5 \times SD$ criterion) or multivariate (Cook's distances < 0.11) detection methods.

For each task, we examined whether children's performance varied by age or gender. Correlation analyses revealed no significant effects between age and accuracy on any task ($ps > .363$). Separate independent-samples t -tests with gender as the between-subjects factor revealed no significant differences between boys and girls on any task ($ps > .229$).

Performance on individual tasks

Analyses of children's performance on the reorientation and area discrimination tasks revealed successful performance, as in the previous experiment. See Table 1 for descriptive data. In particular, children performed above chance (.50) at each ratio of the reorientation task, $ts(59) > 3.69$, $ps < .001$, $ds > 0.48$ (see Figure 3A), with no significant effect of condition, $F(2, 118) = 0.682$, $p = .508$, $\eta_p^2 = .01$, as in the previous experiment, demonstrating an ability to reorient by distance and direction across the different aspect ratios. We further confirmed that children's searches were distributed evenly between the target locations and their geometric equivalents in all conditions ($ps > .214$), ensuring disorientation.

On the area discrimination task, we found that children's performance at all ratios was significantly above chance (.50), $ts(53-59) > 2.31$, $ps < .025$, $ds > 0.31$ (see Figure 3B and Table 1), as in the previous experiment. Moreover, there was a significant effect of ratio, $F(4, 212) = 42.66$, $p < .001$, $\eta_p^2 = .28$, as typically reported (see Supplemental Table 1 for post-hoc comparisons).

An analysis of children's performance on the form analysis task revealed that children performed above the chance level of .17 ($M = .37$, $SD = .17$), $t(59) = 9.16$, $p < .001$. For each test item, the range of performance was .20 – .78.

Figure 3. Results of the reorientation and area discrimination tasks from Experiment 2. (A) Proportion of correct responses at each ratio of the reorientation task (dotted line indicates chance performance). (B) Proportion of correct responses at each ratio of the area discrimination task (dotted line indicates chance performance).

Relations between tasks

Pearson correlation analyses replicated previous effects. In particular, we found a significant correlation between area discrimination and reorientation ability, $r(58) = .28$, 95% CI [.03, .50], $p = .031$ (see Figure 4A), as in Experiment 1 of the present study. We also found a significant correlation between area discrimination and children's performance on the form analysis task, $r(58) = .50$, 95% CI [.28, .67], $p < .001$ (see Figure 4B), as in the study of Bonny and Lourenco (2015). However, there was no significant correlation between children's performance on reorientation and form analysis, $r(58) = -.05$, 95% CI [-.30, .21], $p = .733$ (see Figure 4C), as previously reported by Dillon et al. (2013). See Supplemental Table 3 for all correlations. Effects were largely unchanged when controlling for chronological age (area discrimination $\times$ reorientation: $r = .27$, $p = .034$; area discrimination $\times$ form analysis: $r = .49$, $p < .001$; reorientation $\times$ form analysis: $r = -.05$, $p = .707$).

Figure 4. Correlations between performance on each task in Experiment 2: (A) Area discrimination and reorientation, (B) area discrimination and form analysis, and (C) form analysis and reorientation.

In a subsequent analysis, we tested for the possibility of an indirect relation between reorientation and form analysis. Although there was no significant correlation between the two tasks, it is nevertheless possible that these abilities are indirectly related to one another via a third variable (Hayes, 2012; Kenny et al., 1998; Preacher & Hayes, 2008). Thus, to test this possibility, we conducted a mediation analysis between children's performance on reorientation and form analysis tasks, with their performance on the area discrimination task serving to test for an indirect effect. Confidence intervals for direct and indirect effects were estimated using bias-corrected bootstrapping (5000 resamples). Our conclusions are based on whether or not the limits of the confidence intervals include zero, per recent recommendations (Hayes, 2017).

Consistent with the previous correlation analyses, there was no direct effect between children's reorientation ability and their performance on the form analysis task, $b = -.31$; 95% CI $[-.67, .08]$. By contrast, there were direct effects between children's performance on form analysis and area discrimination, $b = .46$; 95% CI $[.27, .64]$, and between reorientation and area discrimination, $b = .55$; 95% CI $[.10, .96]$. Moreover, and importantly, the indirect effect between reorientation performance and scores on the form analysis task was greater than zero, as revealed by a 95% bias-corrected bootstrap confidence interval based on 5000 resamples $[.07 \text{ to } .49]$, with a point estimate of .25, when including children's magnitude perception in the model. To corroborate this effect, we tested for model misspecification by conducting mediation analyses with either the form analysis or reorientation task as the mediator. There was no support for either variable as a viable mediator (form analysis task: $b = -.17$, 95% CI $[-.42, .02]$; reorientation task: $b = -.06$, 95% CI $[-.21, .01]$).

These findings demonstrate that although there was no direct relation between children's reorientation ability and their performance on the form analysis task, the precision of children's area discrimination nevertheless provided an indirect link between the two. Taken together, these results provide support for a link between systems of navigation and object classification vis-à-vis magnitude perception. Moreover, they suggest a network of

Euclidean geometry understanding in childhood that includes direct and indirect associations between magnitude perception, navigation, and object classification.

General Discussion

How does the human mind represent Euclidean geometry? Given that geometric information is relevant to both navigation and object classification, the answer to this question has the potential to greatly enhance our understanding of a large range of behaviors. A prominent perspective of how Euclidean geometry is represented in the mind (and brain) holds that different geometric properties (e.g., length, angle, and distance) are processed by domain-specific and encapsulated systems of navigation and object analysis. Our results suggest that although such systems are distinct, and may not interact directly with one another, they may nonetheless interface as part of a larger network that includes magnitude perception.

Consistent with a network for representing Euclidean geometry are neuroimaging and patient studies which suggest that cortical areas implicated in processing magnitude information are well situated to interact with regions involved in navigation and object classification. Accumulating evidence demonstrates that the dorsal stream, particularly the posterior parietal cortex (PPC), is important for magnitude perception. Activity in PPC is modulated by ratio effects when comparing magnitude information (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Kadosh et al., 2005; Kaufmann et al., 2005), and disruption of this region (from TMS or stroke) impairs magnitude comparison (Critchley, 1953; Dormal, Andres, & Pesenti, 2012). Importantly, many studies have found broad range functional and structural connectivity between PPC and regions classically implicated in navigation (Kravitz et al., 2011) and object classification (Freud, Rosenthal, Ganel, & Avidan, 2015; Takemura et al., 2015; Van Dromme, Premereur, Verhoef, Vanduffel, & Janssen, 2016).

Nevertheless, the question remains as to *how* systems of navigation, object classification, and magnitude perception might interact to produce the pattern of results in the current study. Because the design of this work was correlational, we cannot provide a definitive answer with respect to causality. However, we discuss two possibilities in an effort to constrain the hypothesis space for future studies.

One scenario is that a magnitude system receives the distinct outputs of navigation and object systems. In this view, domain-specific geometric information is processed independently within navigation (i.e., distance) and object (i.e., length and angle) systems, and is only subsequently used by a magnitude system as needed to solve tasks requiring magnitude perception. This type of organization would not support transfer of geometric information between navigation and object systems and is consistent with the lack of a direct relationship between these systems, reported here and elsewhere (Dillon et al., 2013). However, this type of organization cannot explain cases in which children use geometric cues flexibly across navigation and object systems, reported in previous studies (e.g., Ratliff & Newcombe, 2008b; Yousif & Lourenco, 2017), nor can it explain the indirect effect found in the current study.

An alternative scenario, which we consider more likely, is that a system of magnitude perception is a source of shared *input* to navigation and object systems. In this view, a magnitude system characterizes different geometric properties according to the common property of spatial extent and then deploys this information to systems of navigation and/or object classification as needed. This possibility contrasts with an extreme modular position in which navigation and object classification constitute encapsulated systems subserved by domain-specific inputs (Fodor, 1983). This possibility, however, is consistent with functional specificity within navigation and object systems wherein geometric cues such as distance, length, and angle are used specifically for navigation and object classification. Importantly, this type of organization would explain *both* the lack of a direct relation between navigation and object systems as well as the presence of an indirect relation via magnitude perception. Consistent with this possibility is neural data showing sensitivity to length and angle in regions causally implicated in navigation (Dillon et al., 2017; Julian, Ryan, Hamilton, & Epstein, 2016), as well as distance information in regions causally implicated in object classification (Nag, Berman, & Golomb, 2019; Pitcher, Charles, Devlin, Walsh, & Duchaine, 2009).

Another remaining question is why an indirect effect between navigation and object analysis exists in the absence of a direct effect. Although we cannot provide a definitive answer to this question, we suggest one specific possibility. In particular, there may be additional mediators that suppress the direct relation between navigation and object classification (Hayes, 2009). One such mediator could be cognitive control, which may play a role in the categorization of geometric concepts. For example, although magnitude perception may be critical for discriminating objects, such processing may need to be suppressed when categorizing the objects (cf. Amir, Biederman, & Hayworth, 2012; Tarr & Bülthoff, 1995). That is, two rectangles can be discriminated by the relative lengths of their sides but can only be categorized as the same type of shape by ignoring the sizes of the rectangles (see Figure 1C). And there are other such examples—magnitude perception is necessary when discriminating obtuse angles of different widths but irrelevant when categorizing these angles as obtuse rather than acute. Examining the role of other mediators within a network for geometric processing will be crucial for shedding light on the components and development of this network of reasoning.

The capacity for magnitude perception is present in humans and nonhuman animals in the absence of symbolic experience, and this ability may provide a mechanism by which navigation and object systems flexibly access different types of geometric properties. Based on the relations with magnitude perception in the current study, we suggest that navigation and object analysis may be part of a larger network of Euclidean geometry from early in development. Nevertheless, other research on spatial language (Hermer-Vazquez et al., 2001; Shusterman et al., 2011) and mapping (Dillon & Spelke, 2018; Shusterman, Lee, & Spelke, 2008) suggest alternative mechanisms by which children may use geometric cues flexibly for different purposes. Children's knowledge of spatial-relational words predicted their performance on a navigation task (Hermer-Vazquez et al., 2001) and adults' reorientation performance was disrupted by linguistic interference (Hermer-Vazquez, Spelke, & Katsnelson, 1999; but, see Ratliff & Newcombe, 2008a), suggesting that language may contribute to flexible geometry use beginning at 5-6 years and continuing into

adulthood. Other studies on children's mapping ability suggest a more protracted developmental trajectory in children's use of symbols to support flexible geometry use (Dillon & Spelke, 2018). One explanation for these disparate findings is that magnitude provides children with a rudimentary method to access geometric information from early in development, but this approach is especially susceptible to contextual factors (Learmonth, Newcombe, Sheridan, & Jones, 2008; Yousif & Lourenco, 2017). By contrast, symbolic experience may provide children with a secondary pathway by which to share geometric information, one that may become increasingly more robust as children gain relevant symbolic experience. Future research should consider the extent to which magnitude perception and symbolic experience contribute uniquely to the interactions between navigation and object systems across development. Nevertheless, our findings highlight a previously unexplored avenue by which navigation and object systems may interact within a network for representing Euclidean geometry.

Supplemental Table 1. Post-hoc comparisons between each ratio of the area discrimination task for Experiments 1 and 2. P-values are Bonferonni corrected.

Experiment	Ratio 1	Ratio 2	Mean Difference	<i>t</i>	<i>p</i> _{bonf}
Experiment 1					
	1.11	1.17	.01	0.22	1.000
	1.11	1.25	-.18	-4.89	<.001
	1.11	1.50	-.21	-6.07	<.001
	1.11	2.00	-.25	-6.58	<.001
	1.17	1.25	-.18	-6.42	<.001
	1.17	1.50	-.22	-8.31	<.001
	1.17	2.00	-.26	-9.71	<.001
	1.25	1.50	-.04	-1.18	1.000
	1.25	2.00	-.08	-2.73	.108
	1.50	2.00	-.04	-1.98	.573
Experiment 2					
	1.11	1.17	-.07	-2.12	.389
	1.11	1.25	-.15	-4.61	<.001
	1.11	1.50	-.26	-9.38	<.001
	1.11	2.00	-.31	-11.24	<.001
	1.17	1.25	-.09	-2.86	.060
	1.17	1.50	-.20	-7.78	<.001
	1.17	2.00	-.24	-9.84	<.001
	1.25	1.50	-.11	-3.61	.007
	1.25	2.00	-.15	-5.50	<.001
	1.50	2.00	-.04	-2.39	.207

Supplemental Table 2. Correlations between tasks and between task and age in Experiment 1.

		Reorientation	Area	TRC	Age
Reorientation	Pearson's r	—			
	p-value	—			
Area	Pearson's r	.42	—		
	p-value	.022	—		
TRC	Pearson's r	.00	.35	—	
	p-value	.987	.055	—	
Age	Pearson's r	.32	.33	.18	—
	p-value	.086	.079	.353	—

Supplemental Table 3. Correlations between tasks and between task and age in Experiment 2.

		Reorientation	Area	Form	Age
Reorientation	Pearson's r	—			
	p-value	—			
Area	Pearson's r	.28	—		
	p-value	.031	—		
Form Analysis	Pearson's r	-.05	.50	—	
	p-value	.733	< .001	—	
Age	Pearson's r	.05	.12	.09	—
	p-value	.704	.363	.495	—

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