Becoming Euclid: Connecting Core Cognition, Spatial Symbols, and the Abstract Concepts of Formal Geometry

Becoming Euclid:

Connecting Core Cognition, Spatial Symbols, and the Abstract Concepts of Formal Geometry

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Abstract

Humans alone are capable of formal geometry, like the one outlined in Euclid's *Elements*. We can conceive of points so infinitely small they have no size and lines that extend so infinitely far they never end. And yet, we conceive of such "points" and "lines" without having ever perceived them. Where, then, do such geometric concepts come from? This dissertation asks whether and in what way phylogenetically ancient and developmentally precocious "core" geometric representations guiding navigation and form analysis in humans may come to support uniquely human symbolic and abstract geometric thought. It does so by investigating children's capacity for interpreting the geometric information presented in simple maps and pictures in the context of the scenes and objects that these symbols represent. The dissertation comprises three papers, framed by an introduction and a concluding chapter. *Paper 1* (Dillon, Huang, & Spelke, 2013) investigates whether young children's use of core geometric information to navigate scenes and analyze the shapes of visual forms correlates with their ability to use geometric information presented in simple overhead maps of fragmented triangular environments. *Paper 2* (Dillon & Spelke, 2015) probes the connections between young children's use of core geometry and their interpretation of highly realistic photographs and perspectival line drawings of scenes and objects. *Paper 3* (Dillon & Spelke, 2016) measures the flexibilities, limitations, and automaticity with which children use core geometry when

interpreting pictures of scenes and objects. The concluding chapter reevaluates children's engagement with spatial symbols in light of these three papers, proposing an account of how this engagement changes through development and how such developmental change might provide clues to the origin of abstract geometric reasoning. While the three papers concern children's *comprehension* of the geometry in spatial symbols, the concluding chapter also speculates on how our *production* of spatial symbols might reflect the core systems of geometry and, as a result, might explain a peculiar dearth in the representation of large extended surfaces ("landscapes") throughout the history of human pictorial art.

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Introduction

Humans alone are capable of formal geometry, like the one outlined in Euclid's *Elements*. We can conceive of points so infinitely small they have no size and lines that extend so infinitely far they never end. And yet, we conceive of such "points" and "lines" without having ever perceived them. Where, then, do such geometric concepts come from? In his *Origin of Geometry*, the philosopher Edmund Husserl proclaims: "It is now clear that even if we know almost nothing about the historical surrounding world of the first geometers, this much is certain … it was a world of 'things.'" (Husserl, 1970) Does our capacity for formal, abstract geometry indeed originate in our interactions with the "things" of the physical world? If so, how?

Part of the answer to these questions may lie in two core cognitive systems sensitive to the geometry of the physical world, one dedicated to our navigation through large-scale layouts and one dedicated to our recognition of small-scale objects and visual forms. Both of these core cognitive systems arise early in human development and are phylogenetically ancient: Our abilities to navigate the environment and to recognize the objects in it develop early in life and are shared with diverse animal species. In recent years, intensive study at levels from neurons to cognition (Doeller & Burgess, 2008; Landau & Jackendoff, 1993; Mishkin, Ungerleider & Macko, 1983) has illuminated the geometry guiding these abilities in animals from insects to vertebrates (Chiandetti & Vallortigara, 2008; O'Keefe & Burgess, 1996; Spelke & Lee, 2012; Wystrach & Beugnon, 2009) and in humans from infants to adults (Dehaene, Izard, Pica & Spelke, 2006; Hermer & Spelke, 1996; Newcombe & Huttenlocher, 2003; Schwartz & Day, 1979). When navigating, humans and animals represent their position by absolute distances and directions fixed by the large, extended surfaces in the environment (Lee, Sovrano & Spelke, 2012; Lee, Vallortigara, Flore, Spelke, & Sovrano, 2013; Lever, Wills, Cacucci, Burgess &

O'Keefe, 2002). In contrast, when recognizing objects and visual forms, humans and animals represent the relative lengths and angles that define 3D part structures and 2D shapes (Biederman & Cooper, 1991; Izard, Pica, Dehaene, Hinchey & Spelke, 2011a; Izard & Spelke, 2009).

Despite the pervasiveness and power of these core systems of geometry, neither system alone seems adequate to support the definitions and axioms in Euclid's *Elements*. First, Euclid's definitions require that we engage with abstract and infinite points and lines. For example, Euclid defines "a point" as "that which has no part" and "a line" as "a breadthless length" (Euclid, 1990/300 B.C.E.), whereas our systems for navigation and form analysis evaluate the physical and finite scenes and objects of everyday life.[1] Second, axioms outlined even early in the *Elements* require evaluating how a planar figure's distances and angles relate directly to one another. For example, Book 1, Proposition 32, Corollary 1 proves that the internal angles of a triangle always sum to two right angles (180º). Internal angles must thus maintain this constant sum over changes in the absolute distances of a triangle's three sides over isotropic scaling. But, neither core system represents the relations between distance and angle. Rather, there is representation of distance for navigation or angle for form analysis. Because of the complementary geometric sensitivities of the navigation and form analysis systems, however, together they may provide a foundation for our understanding of Euclidean geometry (Spelke, Lee, & Izard, 2010). The processes by which the geometric contents of these two systems may come to relate to one another, moreover, could reflect a level of flexibility and abstraction that

[1] Brian J. Reilly points out that in Plato's *Meno* (76a) Socrates says, "a shape is the limit of a solid." Reilly's interpretation is that an object's "shape" is the boundary between it and the background, something we *do* see. A representation of that boundary in a drawing will be a line with thickness, but what it represents in the environment is something abstract like a Euclidean line. As a result, we may not perceive Euclidean lines directly, but they may still be based on perception.

mirrors what is needed to reason about the abstract points, lines, and planar figures of Euclidean geometry.

One way to begin to address these suggestions is to examine the geometric content and processes that underlie our earliest-developing uniquely human use of geometric information. Although successful explicit reasoning about the properties of planar figures does not emerge until 10-12 years of age (Dillon & Spelke, in revision; Izard, Dehaene, Pica, & Spelke, 2011b), the use of the geometry presented in spatial symbols, such as simple maps and pictures, spontaneously arises in children as early as 2.5 years. At this age, children can use the relative positions of circles or lines on an overhead map to locate objects or surfaces in a room (Winkler-Rhoades, Carey & Spelke, 2013). Moreover, by age four and with little training or feedback, children can read simple maps that symbolize distance and angle relations in depicted overhead views of an array of surfaces or objects (Huttenlocher & Vasilyeva, 2003; Landau, Dessalegn & Goldberg, 2009; Shusterman, Lee & Spelke, 2008; Vasilyeva & Bowers, 2006). Although other animals display some use of geometric symbols, this use is often limited (Kuhlmeier & Boysen, 2001; 2002; Landau & Lakusta, 2009), requires extensive training (Epstein, 1980; Savage-Rumbaugh, Rumbaugh & Boysen, 1978), and shows no clear evidence that the animals understand a symbol's communicative intent relative to its referent (Bloom & Markson, 1998; DeLoache, 2004; Tomasello & Herrmann, 2010). Thus, investigating children's use of the geometry in spatial symbols may provide our best access to whatever links may be found between our core systems of geometry inherited from other animal species and our later-developing and uniquely human abstract geometric concepts.

This dissertation asks whether and in what way the non-symbolic, core geometric representations guiding navigation and form analysis in humans and other animals may come to support uniquely human symbolic and abstract geometric thought. It does so by investigating children's capacity for relating the geometric information presented in simple maps and pictures to the scenes and objects that these symbols represent. This dissertation comprises three papers, framed by this introduction and a concluding chapter. *Paper 1* (Dillon, Huang, & Spelke, 2013) investigates whether young children's use of core geometric information to navigate scenes and analyze visual forms correlates with their ability to use geometric information presented in simple overhead maps of fragmented triangular environments. *Paper 2* (Dillon & Spelke, 2015) probes the connections between young children's use of core geometry and their interpretation of highly realistic photographs and perspectival line drawings of scenes and objects. *Paper 3* (Dillon & Spelke, 2016) measures the flexibilities, limitations, and automaticity with which children use core geometry when interpreting pictures of scenes and objects. The concluding chapter revaluates children's engagement with spatial symbols in light of these three papers, proposing an account of how this engagement changes through development and how such developmental change might provide clues to the origin of abstract geometric reasoning that relates distance and angle. While the three papers concern children's *comprehension* of the geometry in spatial symbols, the concluding chapter also speculates on how our *production* of spatial symbols might reflect the core systems of geometry and, as a result, might explain a peculiar dearth in the representation of large extended surfaces ("landscapes") throughout the history of human pictorial art.

Core, Symbolic, and Abstract Geometry: State of the Field

Studies in developmental psychology, comparative psychology, and cognitive neuroscience provide evidence for two core systems of geometry that are developmentally precocious (Hermer & Spelke, 1996; Schwartz & Day, 1979; Spelke et al., 2010) and phylogenetically ancient (Cheng, 1986; Chiandetti & Vallortigara, 2008; see Cheng & Newcombe, 2005, and Spelke & Lee, 2012, for reviews). One system, the *navigation* system, represents the layout of the environment by absolute distances and directions fixed by the large, extended surfaces in the environment and measured egocentrically given the navigator's position (Dilks, Julian, Kubilius, Spelke & Kanwisher, 2011; Epstein & Kanwisher 1998; Lee et al., 2012; O'Keefe & Burgess, 1996; Persichetti & Dilks, 2016; Wills, Cacucci, Burgess, & O'Keefe, 2010). This system has been described at a variety of levels of analysis and in a variety of animal species, and its neural correlates have been well-characterized. For example, the hippocampus, a phylogenetically ancient structure in the brain involved in spatial navigation, houses navigationally relevant "place fields," which have been found in rats (O'Keefe, 1976), monkeys (Ono, Nakamura, Fukuda & Tamura, 1991), and humans (Ekstrom et al., 2003). The firing patterns of place fields are determined primarily by the absolute distances of the extended boundaries in an environment along a specified direction (O'Keefe & Burgess, 1996). Moreover, the hippocampus houses a variety of other cell types — boundary cells, grid cells, and head direction cells — which like place fields, are fixed by an extrinsic, allocentric reference frame and which contribute to an organism's recognition of its position and orientation within the larger environment (see Hartley, Lever, Burgess, & O'Keefe, 2014 for a review).

Reliance on absolute distance and directional information for navigation has also been charted behaviorally in a variety of animal species. For example, a seminal study by Cheng & Gallistel (1984) found that rats regain their heading after being disoriented in a rectangular environment using the spatial arrangement of the rectangle's walls, recognizing and searching in one corner location or its diagonal opposite when trying to find food that they had previously observed being hidden. Without training, moreover, rats fail to integrate landmark cues that break the room's geometric symmetry. Studies with zebrafish (Lee et al., 2013), ants (Wystrach & Beugnon, 2009), and bees (Lee, & Vallortigara, 2015), find that these animals exhibit similar search patterns to rats, suggesting that this geometry-based system for navigation is preserved across phylogeny. Indeed, even young children show such patterns when reorienting in rectangular environments. In particular, Lee et al. (2012) used fragmented rectangular and rhomboidal enclosures to tease apart the particular kinds of geometric information young children use reorient. They found that while young children can reorient by large extended surfaces of the same length arranged at distinct distances (forming a fragmented rectangle), they cannot reorient by surfaces of different lengths, equidistant from a center location (forming a fragmented square). Moreover, young children cannot reorient by isolated corner angles placed symmetrically either at distinct distances or equidistant from a center location.

Nevertheless, it should be noted that navigation is not solely supported by distance and directional information, as diverse animal species can also navigate by their position relative to landmarks (see Cheng & Newcombe, 2005, and Spelke & Lee, 2012, for reviews). Landmark-based navigation in humans appears to be neurally dissociated from geometry-based navigation and to require reinforcement learning (Doeller & Burgess, 2008; Doeller, King, & Burgess, 2008). Moreover, young children tend to automatically reorient by the geometry of the environment (e.g., Hermer & Spelke, 1996), even though they can navigate by landmarks when those landmarks are direct cues for where to search (Lee, Shusterman, & Spelke, 2006) or are highly salient (Learmouth, Newcombe, & Huttenlocher, 2001).

While the navigation system based on extended surface geometry is keenly sensitive to absolute distance and directional information in the large-scale layout, the *form analysis* system shows contrasting geometric sensitivities. It represents the shapes of small-scale objects and visual forms by the relative lengths and angles of their edges and parts (Biederman & Cooper 1991; Dehaene et al., 2006; Schwartz & Day, 1979; Smith, 2009). Though the basic neural correlates supporting the analysis of visual forms by their shapes have not been as well characterized as those supporting navigation, neuroimaging studies with human adults have identified regions of high-level visual cortex, such as the inferotemporal cortex (IT) and the lateral occipital complex (LOC; especially anterior-ventral portions like the posterior fusiform sulcus [pFs]), which represent shape over changes in size (i.e., absolute distance) and direction (Dilks et al., 2011; Kayaert, Biederman & Vogels 2003; Kourtzi & Kanwisher, 2000; 2001). Moreover, such regions in the LOC have recently been shown to detect changes in the simple relative lengths and angles, specifically, of box-like objects (Dillon, Persichetti, Spelke, & Dilks, in revision). Neurophysiological studies have corroborated such sensitivities in the primate IT cortex, which houses cells that respond to shape over changes in size, position, and rotation in depth (see Ito et al., 1995; Tanaka, 1997; Tanaka, 2003).

Although 3D object recognition also appears to strongly rely on the presence or absence of non-accidental shape properties, such as part-junctions or edge-curvature (e.g., Biederman, 1987; Biederman, Yu, & Davidoff, 2009), both 3D object recognition and 2D form analysis rely on the further shape-defining metric properties of relative length and angle. The sensitivity to 2D shape information is present across a variety of animal species including rodents (Zoccolan, Oertelt, DiCarlo, & Cox, 2009), pigeons (Blough & Blough, 1997), chicks (Wood, 2013), and bees (Lehrer & Campan, 2005). Newborn infants differentiate among 2D forms by their relative length and angle information given long periods of habituation (Slater, Mattock, Brown, & Bremner, 1991). Nevertheless, during brief exposures to forms with simultaneous variations in the scale, direction, and orientation, only relative length detection persists, suggesting that it might more robustly contribute to early form detection (Dillon, Izard, & Spelke, in preparation). By childhood, humans from diverse cultures predominantly differentiate among 2D visual forms and 3D objects by both relative length and angle information, but not by the directional information that distinguishes a form from its mirror image (Dehaene et al., 2006; Izard & Spelke, 2009; Smith, 2009).

Although these two core systems of geometry show limited sensitivities to the basic geometric information essential to formal geometry, studies in developmental psychology have revealed a contrast between children's performance on tasks assessing their use of core, non-symbolic geometry for navigation and form analysis and their performance on tasks assessing their use of symbolic geometry when interpreting maps and pictures: Children appear to use geometry more flexibly in the symbolic tasks. For example, when children are disoriented in a square room, they fail to use patterns of 2D forms on the walls or on the floor to reorient themselves unless these forms give rise to distance illusions, in which some walls seem farther from the center of the room (Huttenlocher & Lourenco, 2007; Lee & Spelke, 2011; Lee, Winkler-Rhoades & Spelke, 2012b; Lourenco, Addy & Huttenlocher, 2009). However, when maps use 2D forms to symbolize the 3D layout, children are able to use that 2D information to find locations in the layout even in the absence of such illusions (Shusterman et al., 2008; Vasilyeva & Bowers, 2006; Winkler-Rhoades et al., 2013; Uttal & Wellman, 1989). These findings suggest that 2D geometric forms can activate the core system for navigation when the forms are presented as symbols, like overhead maps, but not when the forms are presented as simple surface markings. Additionally, young children fail to use different relative wall lengths of fragmented square rooms when reorienting during a non-symbolic navigation task (Lee, et al., 2012), but children succeed in finding locations in an environment defined only by their relative length information (e.g., finding hiding locations at various points along an extended sandbox) when using a symbolic map of the environment that depicts relative linear extents (Huttenlocher, Newcombe & Vasilyeva, 1999).

All three of the papers in this dissertation evaluate further whether and in what way spatial symbols afford a certain flexibility with geometric information not found in children's use of geometry during non-symbolic tasks. For example, *Paper 1* shows that 4-year-old children can navigate a fragmented triangular environment by just its corner angle information when given a map of the environment, but prior studies have shown that 2-3-year-old children ignore angle information when reorienting without a map in a 3D fragmented rhomboidal room (Hupbach & Nadel, 2005; Lee, et al., 2012). *Paper 2* shows that 4-year-old children can use directional information in 2D forms when those forms are presented as symbolic drawings of a 3D room, but even older children often fail to use directional information when differentiating between non-symbolic 2D visual forms and their mirror images over changes in orientation (Dehaene et al., 2006; Izard & Spelke, 2009). Finally, *Paper 3* shows that children using pictures to guide their search of an environment composed of both extended surfaces and isolated objects flexibly and automatically switch between the two sources of geometric information. Moreover, in exploring the flexibilities found in children's use of spatial symbols, these three papers also evaluate the limits of their use. For example, although children can *switch* between the sources of information that direct their picture-guided search in *Paper 3*, children cannot *combine* the geometric information that describes surfaces and objects, which would allow them to differentiate more effectively between target locations that are better defined by both.

The papers in this dissertation also contribute to a further delineation of the kinds of geometric information children rely on when relating spatial symbols to the scenes and objects that they depict. Several other studies have already suggested that young children use distance and angle to interpret overhead maps (Huang & Spelke, 2015; Huttenlocher & Vasilyeva, 2003; Shusterman, et al., 2008; Vasilyeva & Bowers, 2006; Uttal, 1996; Uttal, Gentner, Liu & Lewis, 2008; Uttal & Wellman, 1989). But by presenting continuous environments and maps with connected figures, these studies have fallen short of specifying the exact geometric information guiding children's performance. For example, Huang & Spelke (2015) presented 4-year-old children with an overhead map of a room in the shape of a 30°-60°-90° triangle and asked them to find target locations in the room that were indicated on the map. Children performed best when the targets were located at the room's most geometrically distinct side or corner (i.e., the 30° angle and the side across from it), indicating that children extracted and used relative distance or angle information when interpreting the layout based on a map. But because the map task in this study used continuous triangular environments, the task could be solved by representing either the distance or angle information that related the depicted triangle in the map to the triangle in the environment (since these types of information are correlated in any planar figure; Euclid, 1990/300 B.C.E.). *Paper 1* uses a similar map task to Huang & Spelke (2015), but presents children with fragmented triangular environments composed of only sides at distinct distances (with gaps at the corners) or only corners of distinct angles sizes (with gaps at the sides) to probe their map reading by distance or angle information alone (after the fragmented-room studies of Lee et al., 2012). Moreover, it adopts an individual differences approach to examine whether the geometric information used during non-symbolic navigation and form analysis might be recruited to read the very same maps in these differently fragmented environments across children. *Paper 2* presents children with tasks aimed to examine their interpretation of similar pictures that represented either a large, extended layout or a small, manipulable object. By means of individual differences and error analyses, *Paper 2* probes the geometric information that might guide children's performance in each context. Finally, *Paper 3* presents children with a single large-scale layout populated by small-scale objects and investigates their use of geometry to interpret pictures that isolate only one type of geometric information, either the extended surface information of the layout or the object information.

The Three Papers

Paper 1 (Dillon et al., 2013)

Previous research by Huang & Spelke (2015) showed that young children's use of absolute distance in a non-symbolic navigation task correlated with their use of a map to locate targets at the surface midpoints of a continuous triangular environment. Moreover, young children's use of relative length and angle in a non-symbolic shape recognition task correlated with their use of a map to locate targets at the corners of the same triangular environment. Because these map tasks used continuous triangular environments, however, both could be solved by representing either the triangle's distances or angles. *Paper 1* investigates whether children's early-emerging core geometric sensitivities to distance, direction, length, and angle make specific contributions to their use of the geometry presented in spatial symbols.

Children were presented with one set of purely geometric maps that served to represent two differently *fragmented* 3D environments. In one map task, children had to navigate a triangular environment in which the corners were removed, leaving three sides of equal length placed at distinct distances and directions from the environment's center. In the other map task, the sides of the triangular environment were interrupted at their centers, leaving three corners of distinct angles. The specific contribution of children's core geometry to their interpretation of the spatial symbols representing these fragmented environments was evaluated by controlling for the effects of age, verbal intelligence, and other spatial abilities.

Forty-five 4-year-old children (23 females; mean age 4;6, range 4;0-4;11) were tested during two laboratory visits. In one visit, children completed two non-symbolic tasks used to elicit core geometric representations in young children and animals. In the navigation task, children were disoriented within three rectangular environments with different aspect ratios and were then allowed to reorient by the distance and directional relations in each environment to locate a hidden object (Hermer & Spelke, 1996; Lee et al., 2012; Lourenco, Huttenlocher, & Vasilyeva, 2005; Newcombe & Huttenlocher, 2003). In the form-analysis task, children were presented with a succession of visual arrays displaying five similar shapes and one shape deviant that differed in one of a variety of properties, including: proportional length; angle size; global shape; relations of parallelism and alignment; and the symmetry and sense relations that distinguish a form from its mirror image (Dehaene et al., 2006). In another visit, children completed two symbolic tasks in which they used the same geometric maps to locate targets in a fragmented triangular environment formed either by walls at distinct distances or by corners of distinct angles. During the map tasks, children were shown maps in which one green dot was depicted, and they were asked to place a stuffed animal on a green dot in the room that matched the green dot in the map. Following the map tasks, children completed a test of verbal intelligence.

Children's non-symbolic navigation depended on the distance and directional relations of the surface layout. In contrast, their non-symbolic analysis of visual forms depended on the size-invariant shape relations of objects. Children's navigation scores predicted their ability to use the maps to locate targets within an environment of surfaces at distinct distances, after controlling for the effects of age, verbal intelligence, form analysis, and performance with the maps in the corner-only environment [$\beta = .320$; $P = .032$]. Children's scores on the form-analysis task predicted their ability to use the same maps to locate targets within an environment of corners of distinct angles, after controlling for the effects of age, verbal intelligence, navigation, and performance with the maps in the side-only environment [$\beta = .322$; $P = .035$]. In addition, even though the two map tasks used identical instructions and map displays, children's performance on these tasks was not correlated [$r(43) = .182$, $P = .230$]. Instead, young children flexibly recruited geometric representations of either navigable layouts or visual forms to interpret the same spatial symbols. These findings thus reveal a link between the early-arising, core geometric representations that humans share with diverse animals and the first signs of human's unique use of geometry to interpret spatial symbols.

Paper 2 (Dillon & Spelke, 2015)

Paper 2 replicates and extends the findings of *Paper 1* by investigating children's use of geometry to interpret highly realistic perspectival drawings and photographs. Unlike overhead maps, perspectival pictures preserve scene and object information from canonical points of view, depicting the junctions of surfaces at angles and the curvature and extent of object contours (Biederman, 1987; Landau, Hoffman, & Kurz, 2006). Young children extract information relevant to object naming (Ganea, Pickard, & DeLoache, 2008) and action imitation (Simcock & DeLoache, 2006) more readily from realistic drawings and photographs than from less iconic line drawings and cartoons. Such findings raise the possibility that children would integrate information from their two core systems of geometry more readily when they view perspectival drawings or photographs than when they view maps or other less iconic spatial symbols.

Experiment 1 (N = 48 4-year-old children, 22 females, mean age 4;6, range 4;0– 4;11) used a placement task as in *Paper 1* to evaluate what geometric information children relied on when interpreting pictures of scenes or pictures of objects. Half of the children saw highly realistic perspectival line drawings of a rectangular room and a Lego object with the same metric properties as the room, and the other half of children saw full-color photographs of the room and object. Children were asked to put a stuffed animal on one location in the room or on the object as indicated by one red dot in each picture. An error analysis of children's responses showed that although error rates were equivalent across contexts, children relied on the distances and directions of extended surfaces when interpreting pictures of the room and on the shape properties of landmarks when interpreting pictures of the object [Context x Error Type interaction, $F(1, 47) = 7.74$, $P = .01$]. In particular, when interpreting pictures of the room, children were likely to err by going to the diagonally opposite location in the room, which presented the same layout geometry (e.g., to the right of the short wall), but different landmark information (e.g., by the door instead of by the window). In contrast, when interpreting pictures of the object, children were likely to err by going to the opposite side of a landmark, using shape information to distinguish among the landmarks, but ignoring the directional information describing the target location's position relative to that landmark (e.g., going to the left of a pyramid-shaped landmark instead of to its right). Experiment 1 also replicated, in children, findings with adults and infants (Biederman & Ju, 1988; DeLoache, Strauss & Maynard, 1979; Shinskey & Jachens, 2014; Walther, Chai, Caddigan, Beck & Fei-Fei, 2011) that the addition of color and texture information in full-color photographs offers no significant advantage over pictures that more simply capture the occluding edges that are essential to spatial vision (Sayim & Cavanagh, 2011; von der Heydt, Peterhans & Baumgartner, 1984).

Experiments 2 and 3 used an individual differences approach (after *Paper 1*) to probe the relations between children's sensitivity to geometry when they interpret symbolic line drawings and when they navigate or analyze visual forms without spatial symbols. Experiment 2 was conducted on the same 4-year-old children who had participated in the navigation, visual form analysis, and map interpretation tasks of *Paper 1*. Children were given a line drawing interpretation task depicting an empty room, similar to that of the scene context in Experiment 1. Children's performance in the line drawing interpretation task correlated with their use of distance and direction during the navigation task [$\beta = 0.28$, $P = .05$] but not with their use of relative length, angle, and global shape on the visual form analysis task [$\beta = 0.05$; $P = .74$]. These results suggest that children recruit representations guiding navigation but not form analysis when interpreting highly realistic perspectival pictures of scenes. Experiment 3 (N = 24 4-year-old children, 11 females, mean age 4;6, range 4;0– 4;11) addressed whether children nevertheless recruit the geometric representations guiding form analysis when interpreting pictures of objects. Indeed, after controlling for age, children's visual form analysis correlated with their performance on the line drawing task depicting objects [$\beta = 0.54$; $P = .02$].

The results from Experiments 1-3 thus suggest that children can use distance and directional information as well as object shape information to interpret perspectival pictures, but also that they are limited in their ability to combine this information to achieve integrated geometric representations of scenes and objects. Such flexibility and limitations are similar to those observed in children's interpretation of overhead maps in *Paper 1*.

Paper 3 (Dillon & Spelke, 2016)

Despite using highly iconic perspectival pictures, *Paper 2* found similar limitations to children's symbol-guided search as *Paper 1*. Nevertheless, the room and object that children explored in *Paper 2* were unusual, and the picture-guided search task did not require that children combine scene-relevant distance and directional information with object-relevant length and angle information to succeed. *Paper 3* thus compared children's ability to find locations in a typical indoor room populated with everyday objects using information from one of three types of perspectival drawings: drawings depicting only the room's extended surfaces; drawings depicting only the objects in the room; and drawings depicting both the room's surfaces and objects together. If children can integrate information about surfaces and objects in drawings, then they should show enhanced abilities to interpret pictures displaying both the extended surface layout and the objects in that layout. In addition, although *Papers 1 & 2* found that children use geometry differentially depending on the context in which spatial symbols are presented, no studies have explored children's awareness of the geometric properties in pictures that make them informative representations. When looking at a picture children might recognize the more informative type of information and then selectively attend to it in the symbol or in the environment to complete the task. Alternatively, children might extract geometric information from spatial symbols automatically whenever these symbols are presented in a particular 3D context. *Paper 3* also aimed to distinguish between these possibilities.

In Experiment 1 (N = 144 4-year-old children, 72 females, mean age 4;5, range 4;0–4;11), children were randomly assigned to see perspectival line drawings of the room depicting just its extended surfaces (i.e., its walls, floor, ceiling), just its objects (i.e., its furniture), or both types of information together. As in prior studies, each picture presented one red dot, and children were asked to place a stuffed animal on the corresponding red dot in the room. For each child, four target red dots occurred at the junctions of extended surfaces in the room, where the room's geometry would be most relevant to finding the target, and four occurred near objects in the room, where that object's shape would be most relevant to finding the target.

Children who saw pictures with extended surface information performed marginally better than children who saw pictures with object information at targets located at the junctions of the extended surfaces in the room [$P = .105$], while children who saw object information performed better at targets near objects [$P = .044$]. Although children who saw both types of information performed better overall compared to each of these groups [compared to children seeing: extended-surface pictures: $P = .037$; object pictures: $P = .009$], their performance at each target location was no better than that of children who saw the more informative of the two types of pictures presenting only one type of information [Ps $> .950$]. These results suggest that children garner no additional benefit of integrating surface and object information to further disambiguate targets during picture-guided search.

Experiment 2 (N = 96 4-year-old children, a subset of those who participated in Experiment 1, 49 female, mean age 4;5, range 4;0– 4;11) evaluated whether children's reliance on the more informative type of geometric information during picture-guided search was driven by explicit attentional mechanisms or was automatic. Children were asked which of two drawings — one depicting just the extended surfaces of the room and one depicting just the objects in the room — they thought better indicated a particular target location, either at a corner of the room or near an object in the room. Children judged that object drawings were more informative [$F(1, 95) = 13.13$, $P < .001$], with no interaction between drawing type and target location [$F(1, 95) = 1.70$, $P = .196$]. For those children who completed both Experiments 1 & 2, there were also no effects of the order in which they completed the experiments, and there was no correlation between successful placement behavior and judgment of the more informative type of information across children.

As in prior studies, children in *Paper 3* failed to integrate navigationally relevant extended-surface distance and directional information with object-recognition-relevant length and angle information to distinguish, for example, between a corner with a chair on its left versus on its right. Moreover, children's higher evaluation of drawings depicting only objects rather than only extended surfaces regardless of target location suggests that this selective use of geometric information appears to operate automatically when a picture is presented in a particular context.

Paper 1: Core foundations of abstract geometry

Dillon, M. R., Huang, Y. & Spelke, E.S. (2013). Core foundations of abstract geometry. *Proceedings of the National Academy of Sciences, 110*(35), 14191-14195.

Abstract concepts of formal geometry underlie a wide range of human achievements, but their source has been debated for millennia (Plato, 1997). Human abilities to navigate the environment and to recognize objects develop early and are shared across diverse animal species. In recent years, intensive study at levels from neurons to cognition (Doeller & Burgess, 2008; Landau & Jackendoff, 1993; Mishkin et al., 1983; O'Keefe & Burgess, 1996) has illuminated the geometric information guiding these abilities in animals from insects to vertebrates (Chiandetti & Vallortigara, 2008; Spelke & Lee, 2012; Wystrach & Beugnon, 2009) and in humans from infants to adults (Dehaene et al., 2006; Hermer & Spelke, 1996; Newcombe & Huttenlocher, 2003; Pyers, Shusterman, Senghas, Spelke, & Emmory, 2010; Schwartz & Day, 1979; Smith, 2009). When navigating, humans and animals represent their position by encoding the distances and directions of extended surfaces in the terrain rather than the angles at which surfaces meet (Lee et al., 2012a; Lever et al., 2002). In contrast, humans and animals represent objects by encoding the angles and relative lengths defining 3D part structures or 2D shapes rather than their absolute sizes or the directional relations that distinguish a form from its mirror image (Biederman & Cooper, 1991; Izard et al., 2011a). Despite the pervasiveness and power of these core geometric representations, neither in isolation is adequate to support abstract geometric intuitions, which require an integrated representation of distance and angle (Dehaene et al., 2006;

Izard et al., 2011b; Spelke et al., 2010). Still, these two sets of core representations together may provide a foundation for abstract geometry.

By the age of 4 years and with little training or feedback, young children can use simple maps that symbolize abstract distance and angle relations by depicting an overhead view of an array of objects or surfaces (Huttenlocher & Vasilyeva, 2003; Landau et al., 2009; Shusterman et al., 2008; Vasilyeva & Bowers, 2006). Not until the age of 6 to 10 years, however, do children begin to integrate distance and angle information when they reason about the properties of triangles and the behavior of dimensionless points and perfectly straight lines of infinite extent (Izard et al., 2011b). Although it is unclear how this ability emerges, examining children's use of geometry in spatial symbols such as overhead maps may shed light on the development of the powerful geometric concepts achieved by adulthood. Uniquely human spatial symbols may serve as a medium in which children engage abstract interpretations of distance and angle. If this early understanding of the abstract geometry in spatial symbols arises from the core geometric foundations that humans share with other animals, young children's map-based navigation should be related to their performance on two distinct tasks eliciting core knowledge of geometry to navigate the environment and to recognize objects. Unlike older children, however, 4-year-old children might fail to integrate the distance and angle information represented in such maps. Previous research by Huang and Spelke (2015) showed that children's use of distance in a non-symbolic navigation task correlated with their use of a map to locate targets at the surface midpoints of a continuous triangular environment. Moreover, children's use of relative length and angle in a non-symbolic shape recognition task correlated with their use of a map to locate targets at the corners of the same triangular environment. Because these map tasks used continuous triangular arrays, however, both tasks could be solved by representing either distance and direction or relative length and angle. In the present research, we investigate whether children's early-emerging and shared geometric sensitivities to distance, direction, length, and angle make specific contributions to their use of the abstract geometry presented in spatial symbols.

We address this question by presenting children with one set of purely geometric maps that serve to represent two differently fragmented 3D environments. In one map task, children had to navigate a triangular array in which the corners were removed, leaving three sides of equal length placed at distinct distances and directions from the array's center. In the other map task, the sides of the triangular array were interrupted at their centers, leaving three corners of distinct angles. Previous research found that children navigated by distance and directional information to find both side and corner locations in fragmented rectangular or rhomboidal arrays displaying equal-length surfaces at distinct distances. In contrast, children failed to use distance, direction, length, or angle to locate targets in a fragmented square array displaying equidistant sides of different lengths or a fragmented rhomboidal array displaying corners at distinct distances with distinct angles (Lee et al., 2012a). Children's failure in this last condition does not stem from a general lack of sensitivity to angle information, however, because even infants, like adults, use similar arrangements of fragmented angles to perceive the shapes of visual forms (Csibra, 2011; Kellman, Yin, & Shipley, 1998). Thus, because absolute length information was held constant across our two map tasks, and because corners were removed in one map task and sides were interrupted in the other map task, the environments presented arrays in which only distance and directional relations or relative length and angle relations, respectively, were available to guide map use (Lee et al., 2012a). We tested the specificity of children's core geometry to interpret the spatial symbols representing these fragmented arrays by controlling for the effects of age, verbal intelligence, and other spatial abilities.

Forty-five 4-year-old children (23 female, mean age = 4 years 6 months, age range = 4 years 0 months – 4 years 11 months) were tested during two laboratory visits. In one visit, they completed two non-symbolic tasks used to elicit core geometric representations in young children and animals. In the navigation task, children were disoriented within three rectangular environments with different aspect ratios and then were allowed to reorient by the distance and directional relations in each environment to locate a hidden object (Hermer & Spelke, 1996; Lee et al., 2012a; Lourenco et al., 2005; Newcombe & Huttenlocher, 2003) (Fig. 1.1*A*). In the visual form analysis task, children were presented with a succession of visual arrays displaying five similar shapes and one deviant shape that differed in one of a variety of properties, including proportional length, angle size, global shape, relations of parallelism and alignment, and symmetry, as well as the sense relations that distinguish a form from its mirror image (Dehaene et al., 2006) (Fig. 1.1*B*). In another visit, children completed two symbolic tasks in which they used the same geometric maps (Fig. 1.2*A*) to locate targets in a triangular array formed either by walls at distinct distances (Fig. 1.2*B*) or by corners of distinct angles (Fig. 1.2*C*). Following the map tasks, children completed a test of verbal intelligence.

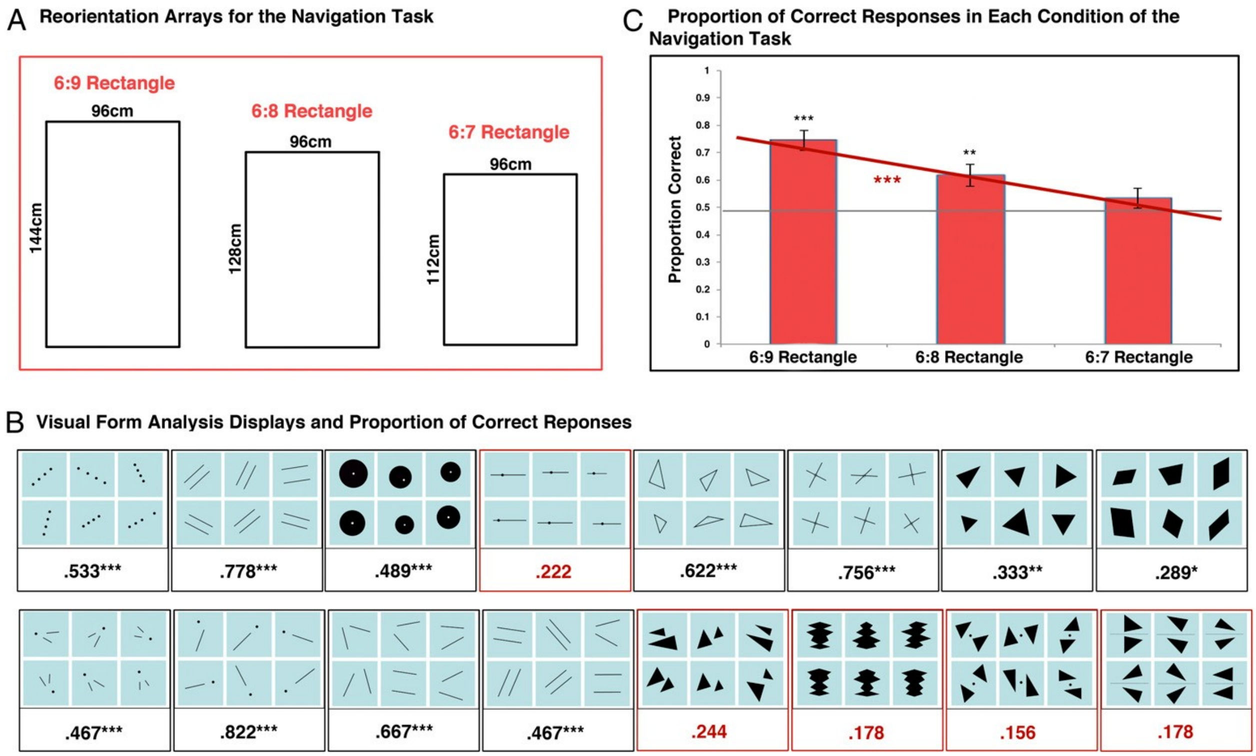

Fig. 1.1 Two non-symbolic geometry tasks. (*A*) Schematics of the three rectangular enclosures that were used in the navigation task. (*B*) All 16 displays used in the visual form analysis task, which required children to locate the geometric deviant in a group of shapes. Children performed above chance in 11 of the 16 trials and at chance in the five trials outlined in red (binomial test: $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$). (*C*) Proportion of correct responses in each condition of the navigation task. Children performed above chance in both the 6:9 and 6:8 conditions. They used the enclosures' relative wall distances with greater difficulty as their aspect ratio approached 1 ($^{***}P < 0.001$; $^{**}P < 0.01$).

Performance on the tests of reorientation and form analysis was consistent with past research using these tasks with infants and animals. On the reorientation task, children searched most often and equally at the correct and opposite corner locations, indicating that they were disoriented (Fig. 1.1*C* and Table S1.1) and that they used the distance and directional relations in the enclosure to reorient themselves. Children's performance exceeded chance in the two more elongated rectangular enclosures (6:9 rectangle [$t(44) = 6.64$, $P < 0.001$] and 6:8 rectangle [$t(44) = 2.85$, $P = 0.007$]) but not in the least elongated enclosure (6:7 rectangle [$t(44) = 0.88$, $P = 0.382$]). Finally, children used distance relations with greater difficulty as the relative distances of the extended surfaces became harder to distinguish [$F(1, 44) = 21.42$, $P < 0.001$; Fig. 1.1*C*]. Reorientation scores were calculated as an average of the two above-chance conditions. Children successfully located the deviant shape on 11 of the 16 form analysis trials (Fig. 1.1*B*). They performed at chance in two trials assessing their sensitivity to the sense relations that distinguish a form from its mirror image, two trials targeting their sensitivity to symmetry, and one trial presenting forms characterized by both relative length and angle but varying considerably in size. An analysis of error patterns from this task revealed that most children relied on absolute size rather than shape in this last case, choosing the smallest figure significantly more often than any other figure in the array (Fig. 1.1*B*). In all the above- chance trials, the deviant form differed from the others by one or more geometric properties, including proportional length, angle size, global shape, or relations of parallelism and alignment; forms that shared these properties varied in absolute size, orientation, or both. Children's form analysis scores were calculated as an average of the 11 above-chance trials.

On the map tasks, children were successful overall when the map designated target locations in an array with walls at distinct distances [$t(44) = 8.61$, $P < 0.001$] and with corners of distinct angles [$t(44) = 5.34$, $P < 0.001$]. Performance did not differ significantly between these tasks [$t(44)$ 1.70, $P = 0.096$] or between trials in which targets appeared directly at a side or corner location and trials in which targets appeared at the gap between two sides or two corners [$t(44) = 0.063$, $P = 0.950$]. As was the case with reorientation, children's performance scaled with the geometric distinctiveness of the target locations; children successfully located targets on all six of the distance map trials and on three of the six angle map trials (Fig. 1.2 *D* and *E*). Children's distance and angle map scores were calculated as an average of their performance on the above-chance trials.

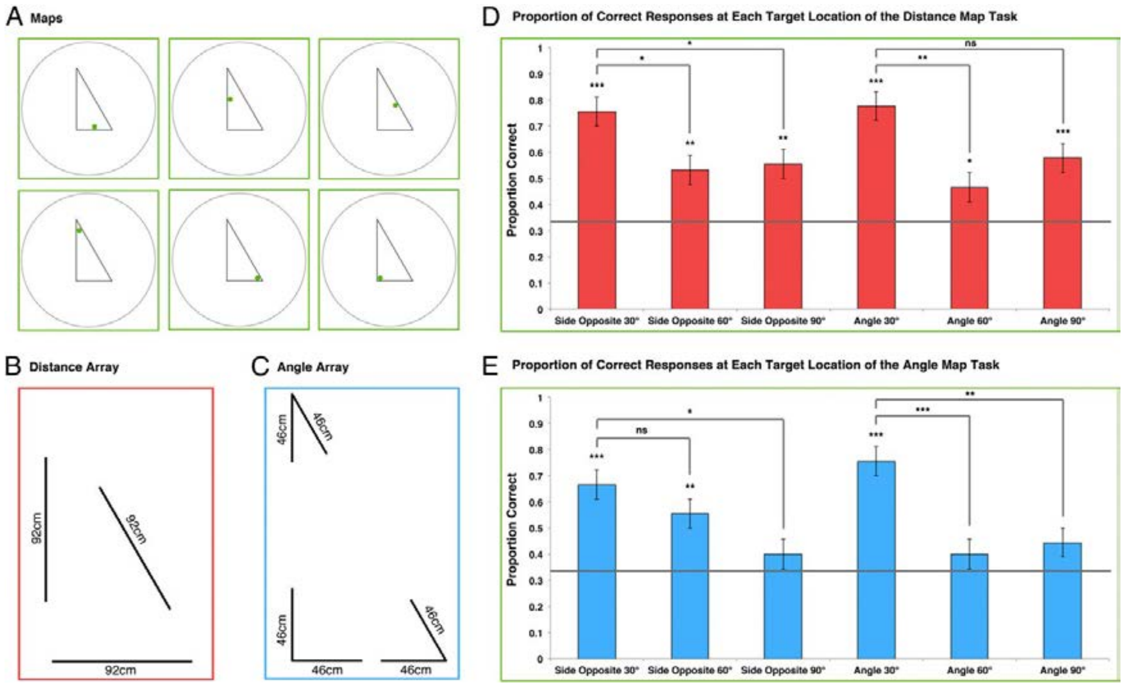

Fig. 1.2. Maps and schematics of the 3D environments in the two map tasks. (*A*) Six maps used in both map tasks, which depicted intact triangles at a 0.13:1 scale. Each map was presented at a constant orientation relative to the child, who faced a different direction relative to the array on each trial (0°, 60°, 120°, 180°, 240°, or 300°). (*B*) Overhead view of the triangular array for the distance map task. Three boards of white foam core (25 cm × 92 cm) were arranged as the sides of a 30-60-90 triangle (102 cm × 176.67 cm × 204 cm). (*C*) Overhead view of the triangular array for the angle map task. Three corners of white foam core (25 cm high) were arranged as the corners of a 30-60-90 triangle with two 46-cm segments defining each corner. Proportion of correct responses at each target location in the distance map task (*D*) and the angle map task (*E*). The gray horizontal line indicates chance-level (0.33) performance (binomial test: ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$). In both tasks, more correct responses occurred at the most geometrically distinct locations, indicating that children were using this geometric information when searching for targets (McNemar test: ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$).

We first tested for relations between children's use of core geometry for navigation and visual form analysis. Strikingly, a bivariate correlation revealed no significant association between performance on the reorientation task and performance on the form analysis task [$r(43) = 0.026$, $P = 0.867$; Fig. S1.1]. Thus, children's use of geometry for navigation showed no evidence of being related to their use of geometry for analyzing visual forms.

Do children nevertheless engage these different core geometric representations when interpreting the same spatial symbol? We conducted hierarchical regression analyses to address this question. The first analysis tested whether children recruited representations of distance as used for navigation when finding targets in the distance map task. Children's reorientation scores predicted their ability to use the map to locate targets within an array of surfaces at distinct distances, over and above the effects of age and verbal intelligence [β(Reorientation) = 0.334, $P = 0.027$; Fig. 1.3*A*]. Still, it is possible that children used multiple strategies for locating targets in the distance map task. To test for the specificity of children's reorientation ability as a predictor of their score on the distance map task, we further controlled for children's performance on both the visual form analysis task and the angle map task. Children's performance on the visual form analysis task did not significantly predict their performance on the distance map task [β(Form Analysis) = 0.255, $P = 0.104$], and their reorientation scores still predicted a significant amount of variance after controlling for individual differences in visual form analysis and in performance on the angle map task [β(Reorientation) = 0.320, $P = 0.032$].

The second analysis tested whether children recruited representations of relative length and angle as used for object recognition when finding targets in the angle map task. Children's scores on the visual form analysis task predicted their ability to use the same maps to locate targets within an array of corners of distinct angles, over and above the effects of age and verbal intelligence [β(Form Analysis) = 0.325, $P = 0.023$; Fig. 1.3*B*]. To test for the specificity of children's visual form analysis as a predictor of their score on the angle map task, we further controlled for children's performance on both the reorientation task and the distance map task. Children's performance on the reorientation task did not significantly predict their performance on the angle map task [β(Reorientation) = 0.034, $P = 0.825$], and their ability to analyze visual forms still predicted a significant amount of variance after controlling for individual differences both in reorientation and in performance on the distance map task [β(Form Analysis) = 0.322, $P = 0.035$].

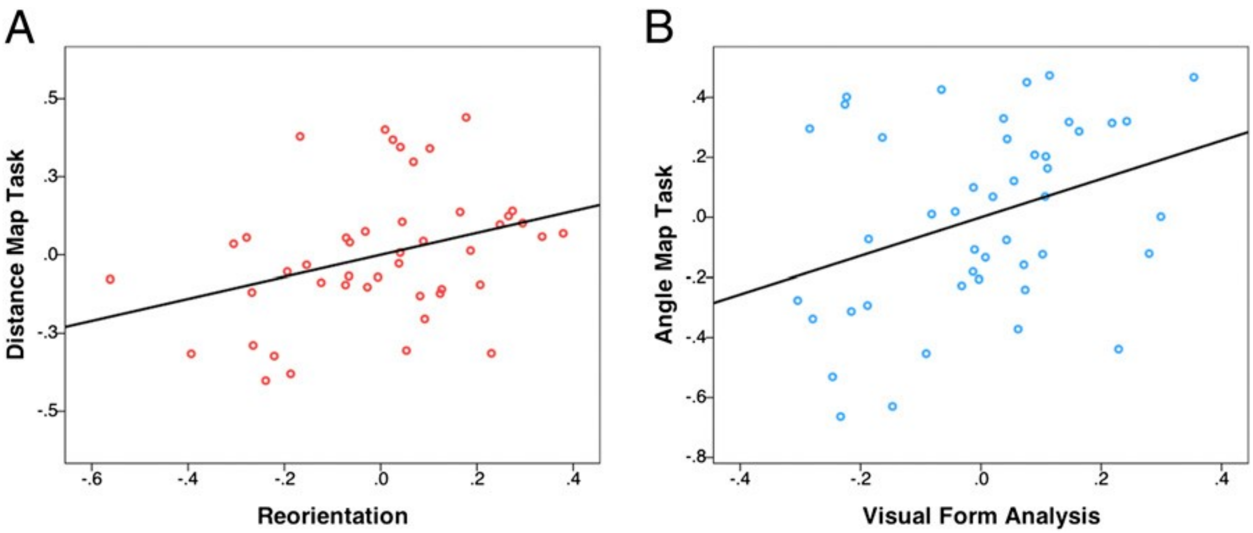

Fig. 1.3. Partial regression plots controlling for the effects of age and verbal intelligence and showing that reorientation performance predicted performance on the distance map task (*A*) and visual form analysis performance predicted performance on the angle map task (*B*).

These analyses reveal a striking pattern of relations between children's reliance on distance for both the reorientation and distance map tasks and their reliance on object shape information for both the visual form analysis and angle map tasks. To investigate whether the two map tests elicited any common processes, we tested for a relation between children's performance on the two map tasks. A bivariate correlation revealed no significant association between performance on the distance and angle map tasks [$r(43) = 0.182$, $P = 0.230$; Fig. S1.2]. Although the two map tasks used identical instructions and map displays to test children's interpretation of symbolic geometry, the children recruited different representations in applying the map to two different 3D environments.[2] Consistent with past findings that young children fail to integrate relations of distance and angle in tests probing more abstract geometric intuitions (Izard et al., 2011b), children in the present studies showed no evidence of integrating core geometric representations used for navigation and form analysis when interpreting simple symbolic geometric maps.

[2] When targets were hidden at a side in the distance map task, our analyses and past research (Landau & Lakusta, 2009; Lee et al., 2012a) suggest that children located targets by relying on their distance to the sides of the array. When targets were hidden at a corner in the angle map task, children located targets by relying on the angle sizes of the array corners (Landau & Lakusta, 2009; Lee et al., 2012a) (Fig. 1.2*D*). It is less clear what geometric information children used when finding targets located at the gaps in the arrays. In the distance map task, children may have located a corner target either by finding a location to the left or to the right of a side at a particular distance or by finding a location between two sides at particular distances. In the angle map task, searches to the side locations likely did not depend on the distance relations between the corner locations. Children's performance on the side locations in the angle map task correlated with their performance on the corner locations of the angle map task (Spearman's $\rho = 0.300$, $P = 0.045$) and not with their performance on the side locations in the distance map task (Spearman's $\rho = 0.040$, $P = 0.793$). Nevertheless, children may have located the side between two corners either by inferring the relative length (rather than the absolute distance) of the side implied by two corners or by evaluating the relative sizes of the two corner angles themselves. Further research is needed to distinguish between these possibilities.

In summary, performance on tasks engaging children's early-arising, non-symbolic knowledge of geometry specifically predicted performance on two tasks evaluating their use of spatial symbols. Children's sensitivity to distance and directional relations in a navigation task predicted their use of a map to find targets in a 3D array with surfaces at distinct distances; their sensitivity to properties of object shapes in a form analysis task predicted their use of the same map to find targets in a 3D array with corners of distinct angles. This pattern of findings provides evidence that in their untutored interpretations of symbolic maps, children flexibly recruit the core geometric representations that emerge in infancy (Hermer & Spelke, 1996; Landau, Gleitman, & Spelke, 1991; Lourenco & Huttenlocher, 2008; Newcombe & Huttenlocher, 2003), are shared by other animals (Chiandetti & Vallortigara, 2008; Chiandetti & Vallortigara, 2010; O'Keefe & Burgess, 1996; Wills et al., 2010), and are used by children and adults throughout their lives.

Children's performance on both non-symbolic tests of navigation and form analysis and symbolic tests of map understanding show no evidence of integrated representations of distance and angle. Such integration would have been indicated by convergent use of geometry in both of the symbolic spatial tasks and would have enhanced children's performance on all the tasks. For adults, who have achieved more abstract Euclidean intuitions, a triangle can be described by the distances between its corners, by the angles at its corners, or by a triplet of distance and angle combinations. Adults are sensitive to these geometric relations and likely would apply the same shape description to all the arrays used in our symbolic map tasks (Fig. 1.2 *C* and *D*). Nevertheless, 4-year-old children show no evidence of having constructed the abstract geometric concepts that relate distances to angles and that specify shape descriptions applying to both surfaces and corners, even when reading spatial symbols, a skill achieved early in development

(Deloache 1987; 1991). Research using the present methods with older children applied to tasks engaging abstract geometry that develops over the lifespan may offer clues to the processes by which these integrated and uniquely human geometric intuitions emerge.

Materials and Methods

Participants

Children participated in the two testing sessions within a 2-week time window. Three additional children participated in at least one task but were excluded due to a misunderstanding of task directions (2) or failure to return for the second appointment (1). Twenty-three children completed the set of non-symbolic tasks on their first visit (followed by the set of symbolic tasks on their second visit), and 22 children completed these sets of tasks in the opposite order. There were no performance differences be- tween these two groups (Table S1.2) or between male and female children on any of the tasks or conditions (Table S1.3). Informed consent was obtained from all participants. The use of human subjects was approved by the Committee on the Use of Human Subjects at Harvard University.

Statistical Methods

Reliability of the measures subject to regression and correlational analyses was maximized by the following: randomizing task order; selecting tasks, items, and difficulty levels based on research investigating human navigation, form analysis, and map reading (Dehaene et al., 2006; Izard & Spelke, 2009; Lee et al., 2012a; Lourenco et al., 2005; Shusterman et al., 2008; Vasilyeva & Bowers, 2006); excluding measures yielding chance performance; and confirming that mean performance levels and observed variance were similar across tasks and conditions (Chapman & Chapman, 1978) (Table S1.4). As confirmation that parametric hierarchical regressions were appropriate for these data, approximate normality of regression residuals was confirmed on the basis of comparison with the standard bell curve and examination of Q–Q plots.

Reorientation

Both the experimenter and the child stood inside one of three 50-cm-high rectangular enclosures made of white foam core and differing only in aspect ratio (Fig. 1.1*A*). Each enclosure was placed in the center of a round room with white paneled walls, symmetrical lighting, and a concealed spring-loaded door (providing no distinguishing landmark or geo- metric information). For each of the four trials of each condition, the experimenter hid a sticker under a disk at one corner location of the rectangle while the child watched. Then, the experimenter blindfolded the child, turned him or her around in place for three to four full rotations until the child was disoriented, and stopped the child facing the center of one wall (a different wall on each trial). Finally, the participant removed the mask and searched for the sticker. The hiding locations were constant across all trials and conditions for any given child but were counterbalanced across children; the order of the three conditions also was counterbalanced across children. Children's search locations (measured as the first lifted disk) were judged offline from an overhead video feed by observers who were un- aware of the children's performance in any of the other tasks. A single summary variable of successful use of geometry (proportion of searches to the two geometrically correct corners) was computed across the two conditions yielding above-chance performance.

Visual Form Analysis

Children were presented with 16 trials on a computer screen, each trial depicting an array of six 2D shapes. They were asked to examine all the shapes and to locate the shape that did not belong with the rest. In each array, five of the shapes were similar with respect to proportional length, angle size, global shape, parallelism and alignment, or left/right symmetry, whereas one shape differed on that property (Fig. 1.1*B*). Trials were randomly intermixed during the testing session. After a child indicated his or her choice on the screen, an experimenter, who was unaware of the child's performance on the other tasks, pressed the associated key on the keyboard and the response was recorded by the presentation software. Although children were not given instructive feedback during the testing session, they did complete and receive feedback on two practice trials, using figures that did not differ on the target properties, to ensure that the task was understood. A summary variable of children's scores on the visual form analysis task was calculated based on an average of the 11 above- chance trials.

Map-Based Navigation

For each map task, the child stood in the center of a triangular array composed of sides (distance task) or corners (angle task) while the experimenter showed him or her a continuous triangle depicting the shape of the array from an overhead view (Fig. 1.2*A*). Because the same complete shape was depicted for both side and corner arrays, children viewed the same maps in both tasks. All maps were presented at a constant orientation with the 30° angle at the top, but for each trial, the child faced a different direction relative to the array (0°, 60°, 120°, 180°, 240°, or 300°). A child indicated his or her choice by putting a small stuffed animal on one of six green caps located either at the corners of the triangle formed by the array or at the centers of the sides of the array. Because the arrays were fragmented, targets were located at an environmental feature, a physically present side or corner, on only three trials in each task. On the other three trials, targets were located at the gap between two environmental features (i.e., at the corner formed by the continuation of two flanking sides or at the side formed by the continuation of two flanking corners). Corner and side target locations were tested in blocks, with block order, map task order, and map orientation counterbalanced across children. Before each map task, two practice trials were presented, using color rather than geometry to specify a target location: The child had to find either a purple or pink cap in the center of the room after the experimenter pointed to either a purple or pink dot in the center of a laminated sheet of paper that depicted nothing else. Performance was assessed from an overhead video feed by observers who were unaware of the child's performance on other tasks. The proportion of correct responses was calculated separately for each of the two tasks, and a summary variable was calculated based on targets where children showed above-chance performance.

Supporting Information

Evidence for Disorientation and Use of Geometry in Reorientation

In the reorientation task, children were disoriented in three rectangular rooms with different aspect ratios (6:9, 6:8, and 6:7). To confirm that children were disoriented and used the distance relations in each room to find targets, we compared their searches to the correct corner with those of the diagonally opposite corner (the correct corner's geometric equivalent). We found no difference between searches to the correct and geometrically equivalent corners in any of the conditions (Table S1.1), indicating that children were disoriented before searching and used the shape of the room to find targets.

No Order or Sex Effects

Because we evaluated children's performance on a number of non-symbolic and symbolic tasks of geometric knowledge in addition to a test of verbal intelligence, we split these tasks into two sessions. Twenty-three children received the non-symbolic tasks on their first visit, followed by the set of symbolic tasks and a verbal intelligence test on their second visit; 22 children received these sets of tasks in the opposite order. We found no performance differences between these two groups (Table S1.2) or between male and female children on any of the tasks or conditions (Table S1.3).

Statistical Reliability

Tasks and items for all measures entering into the regression or correlational analyses were chosen based on previous research in the domains of human navigation, visual form analysis, and map reading (Dehaene et al., 2006; Izard & Spelke, 2009; Lee et al., 2012a; Lourenco et al., 2005; Shusterman et al., 2008; Vasilyeva & Bowers, 2006). Each task was designed at a difficulty level to permit a mean score between chance and 100%, with no floor or ceiling effects. Mean performance was similar across all measures (between 57% and 68% correct), and observed variances were well matched (Table S1.4), supporting the use of these measures in an individual differences approach (Chapman & Chapman, 1978).

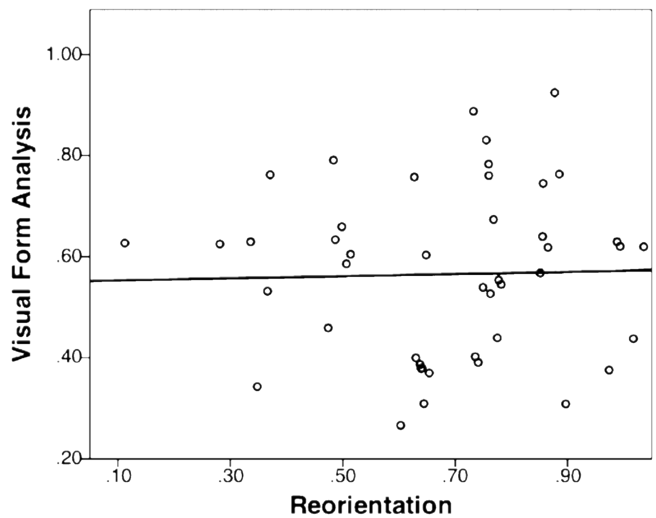

Fig. S1.1. Scatterplot depicting the non-significant relation between children's performance on the reorientation task and the visual form analysis task.

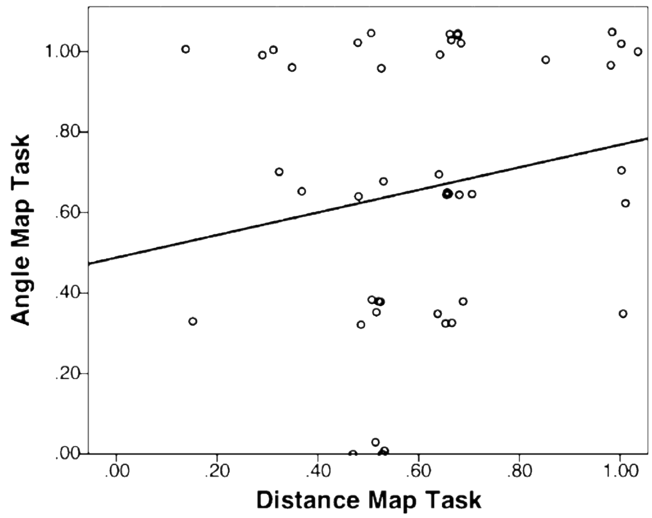

Fig. S1.2. Scatterplot depicting the non-significant relation between children's performance on the distance map task and the angle map task.

Table S1.1. Proportion of responses to the correct corner or its geometric equivalent in the three enclosures of the reorientation task.

Enclosure	Correct corner	Geometric equivalent	Significance test
6:9 Rectangle	0.39	0.35	$t(44) = 0.79$, $P = 0.434$
6:8 Rectangle	0.33	0.28	$t(44) = 0.84$, $P = 0.407$
6:7 Rectangle	0.26	0.27	$t(44) = -0.22$, $P = 0.828$

Table S1.2. Means and significance tests for performance differences between those children who completed the set of non-symbolic tasks on their first visit (followed by the set of symbolic tasks on their second visit) and those children who completed these sets of tasks in the opposite order.

Task	Non-symbolic first	Symbolic first	Significance test
Reorientation	0.60	0.66	$t(43) = -1.05$, $P = 0.299$
Visual form analysis	0.57	0.56	$t(43) = 0.17$, $P = 0.863$
Distance map	0.57	0.65	$t(43) = -1.30$, $P = 0.202$
Angle map	0.56	0.75	$t(43) = -1.98$, $P = 0.054$
Peabody Picture Vocabulary Test	115.64	120.34	$t(43) = -1.46$, $P = 0.153$

Table S1.3. Means and significance tests for performance differences between male and female children.

Task	Male children	Female children	Significance test
Reorientation	0.64	0.63	$t(43) = 0.23$, $P = 0.821$
Visual form analysis	0.55	0.59	$t(32.56) = -0.76$, $P = 0.451$
Distance map	0.67	0.55	$t(43) = 1.95$, $P = 0.058$
Angle map	0.58	0.74	$t(43) = -1.66$, $P = 0.105$
Peabody Picture Vocabulary Test	116.05	119.96	$t(43) = -1.20$, $P = 0.237$

Table S1.4. Means and variances for each of the measures entering into regression or correlational analyses.

Task	Mean	Variance
Reorientation	0.68	0.04
Visual form analysis	0.57	0.03
Distance map	0.61	0.05
Angle map	0.66	0.11

Paper 2: Core geometry in perspective

Dillon, M. R., & Spelke, E. S. (2015). Core geometry in perspective. *Developmental Science*, *18*(6), 894-908.

Introduction

Line drawings – two-dimensional (2D) representations of three-dimensional (3D) scenes and objects – are universally perceptible across human cultures (Kennedy & Ross, 1975), appear early in human prehistory (Biederman & Kim, 2008; Clottes, 2008), and pervade the environments of young children in modern societies (DeLoache, 2004). Embedded in these drawings are the inherent geometries that capture the scenes and objects in our 3D world (Gombrich, 2000). Although much research has explored children's understanding of the symbolic function of line drawings and other pictures (DeLoache, 1987, 1991, 2004), little research has probed how children use the geometric properties of line drawings to interpret the scenes and objects that they represent. Such research is important because previous studies have linked children's use of the geometry in one kind of spatial symbol – overhead purely geometric maps – not only to the geometric representations humans share with other animals (Dillon, et al., 2013; Landau & Lakusta, 2009; Uttal, 2000; Vasilyeva & Bowers, 2006), but also to the abstract geometric understanding that is unique to humans (Dillon & Spelke, in revision). Still, young children show limits in their use of geometry during map reading, which may result from the unusual viewpoints that such maps present. Questions thus remain regarding whether and in what way highly realistic perspectival pictures might engage these geometric systems. Answers to such questions may reveal how spatial symbols in general, and realistic drawings in particular, link our limited shared geometric capacities to the highly complex geometric intuitions that form the foundation of uniquely human science and mathematics.

Studies in developmental psychology, comparative psychology, cognitive neuroscience, and other fields provide evidence for two core systems of geometry that are phylogenetically ancient (Cheng, 1986; Chiandetti & Vallortigara, 2008; see Cheng & Newcombe, 2005, and Spelke & Lee, 2012, for reviews) and early emerging (Hermer & Spelke, 1996; Landau & Jackendoff, 1993; Schwartz & Day, 1979; Spelke et al., 2010). One system represents the layout of the environment by encoding the distances and directions of its extended surfaces (Dilks et al., 2011; Epstein & Kanwisher 1998; Lee, et al., 2012; O'Keefe & Burgess, 1996; Wills et al., 2010). The other system represents the shapes of objects by encoding the relative lengths and angles of their edges, as well as their major and minor axes (Biederman & Cooper 1991; Dehaene et al., 2006; Schwartz & Day, 1979; Smith, 2009). These systems activate different brain regions (Dilks et al., 2011; Dilks, Julian, Paunov & Kanwisher, 2013; Epstein & Kanwisher, 1998) and rely on different information (Schyns & Oliva, 1994).

Developmental research has revealed a contrast between children's limited use of geometry in tasks assessing non-symbolic abilities for navigating scenes and recognizing objects and their more flexible use of geometry in the symbolic realm. For example, when children are disoriented in a symmetrical room, they fail to use patterns of 2D forms on the walls or the floor to reorient themselves unless these forms give rise to perceptual asymmetries in the 3D layout (Huttenlocher & Lourenco, 2007; Lee & Spelke, 2011; Lee et al., 2012b; Lourenco et al., 2009). When maps use 2D forms to symbolize a 3D layout, however, children are able to use that 2D information to find locations in the layout (Shusterman et al., 2008; Vasilyeva & Bowers, 2006; Winkler- Rhoades et al., 2013; Uttal & Wellman, 1989). These findings suggest that 2D geometric forms can activate the core system for navigation when the forms are presented as symbols, like overhead maps, but not when the forms are presented as surface markings in non-symbolic tasks. These studies do not reveal, however, what geometric information children rely on when using maps or pictures to find locations in the environment.

Other studies have begun to address this question, providing evidence that young children use relations of distance or angle to interpret overhead maps (Huttenlocher & Vasilyeva, 2003; Shusterman et al., 2008; Vasilyeva & Bowers, 2006; Uttal, 1996; Uttal et al., 2008; Uttal & Wellman, 1989). For example, Huang and Spelke (2015) presented 4-year- old children with an overhead map of a room in the shape of a 30-60-90 triangle and asked them to find locations in the room that were indicated on the map. Children performed best when targets were located at the room's most geometrically distinct side or corner (the 30° angle and the side across from it), indicating that they extract and use relative distance or angle information when interpreting a layout based on a map.

Both Huang and Spelke (2015) and Dillon et al. (2013) adopted an individual differences approach to probe the relations between children's sensitivity to distance and angle when they navigate, recognize objects, and interpret spatial symbols. Dillon et al. (2013) presented 4-year-old children with overhead maps of fragmented triangular rooms: One room consisted only of the triangle's sides, which isolates the distance and directional information children use to specify locations in the navigable layout; and the other consisted only of the triangle's corner angles, which isolates the angle information children use to specify the shapes of landmark objects (Lee et al., 2012a). Children's success in the side-only room was predicted by their performance on a non-symbolic task assessing navigation by distance and direction. Moreover, children's success in the corner-only room was predicted by their performance on a non-symbolic task assessing shape analysis by relative length and angle. Nevertheless, children's ability to interpret the same maps in these two different contexts was uncorrelated. These findings suggest that children's interpretation of maps can depend on non-symbolic geometric information from either of their core systems of geometry, depending on the context in which the maps are presented (Dillon et al., 2013).

The findings from these studies probing young children's understanding of overhead maps may nevertheless underestimate children's geometric competence, as the ability to recognize 3D shape information in line drawings presenting familiar views appears very early in human development. Nine-month-old infants are able to recognize objects in line drawings that depict edge-based contour information without the addition of any color or texture cues (Jowkar-Baniani & Schmuckler, 2011; Shinskey & Jachens, 2014). Unlike maps, perspectival line drawings preserve scene and object information from canonical perspectives, depicting the junctions of surfaces at angles and the curvature and extent of object contours (Biederman, 1987; Landau et al., 2006). Young children extract information relevant to object naming (Ganea et al., 2008) and action imitation (Simcock & DeLoache, 2006) more readily from realistic drawings and photographs than from less iconic line drawings and cartoons. All these findings raise the possibility that children will integrate information from their two core systems of geometry more readily when they view perspectival drawings or photographs than when they view maps or other less iconic spatial symbols.

The present experiments therefore examine whether and how the geometry embedded in 2D perspectival pictures engages our early-emerging systems for navigating the environment and recognizing objects. We ask whether such representations facilitate more integrated geometric representations of scenes and objects than do overhead maps. Experiment 1 used a within-participants object placement task to evaluate what geometric information children rely on when interpreting pictures of scenes or pictures of objects. We investigated patterns in children's correct and erroneous responses to determine whether they relied on the distances and directions of extended surfaces and on the shape properties of landmarks in each context. Experiment 1 also sought to replicate, in children, findings with adults and infants (Biederman & Ju, 1988; DeLoache et al., 1979; Shinskey & Jachens, 2014; Walther et al., 2011) that the addition of color and texture information in full-color photographs offers no significant advantage over pictures that more simply capture the occluding edges that are essential to spatial vision (Sayim & Cavanagh, 2011; von der Heydt et al., 1984). Experiments 2 and 3 used an individual differences approach (after Huang & Spelke, 2015; Dillon et al., 2013) to probe the relations between children's sensitivity to geometry when they interpret symbolic line drawings and when they navigate or recognize objects without spatial symbols. Because of the greater familiarity of perspectival views of scenes and objects, children might engage geometric information in a more integrated fashion when interpreting line drawings than when interpreting overhead maps. Alternatively, because line drawings transform 3D geometry into two dimensions and serve as symbols early in development, just as maps do, children may treat them similarly and recruit each system of core geometry based on the context in which they are presented.

Experiment 1

In Experiment 1, we investigated whether 4-year-old children would use pictures – line drawings or photographs – of a novel room and a novel object to locate places either in the room or on the object. The room and object differed in some visual properties, but were geometrically similar and comprised surfaces of similar relative shapes and sizes. In addition, each context preserved essential scene or object properties: scenes are typically large, concave, and navigable, whereas objects are typically small, convex, and manipulable. The room was a standard indoor environment emptied of furniture. We used Lego pieces to construct the object because Lego constructions and pictures of Lego constructions are familiar to children. Moreover, Lego constructions can capture the same geometric relations as a room, and they have been found to elicit these geometric representations reliably in adults (Epstein & Kanwisher, 1998). Thus, the Lego object was likely to be interpreted by children as a manipulable object rather than as a small-scale navigable layout, and it captured much of the same geometric structure as the room.

During the experiment, children stood in the depicted room or sat at a table facing the depicted object. They then were shown a picture of the room or the object and asked to place a toy at a location in the room or on the object as indicated by a dot in the picture. Across trials, children viewed pictures of the room or object from different perspectives (all at eye level and upright, but varying in facing direction) and specifying different placement locations. By analyzing children's successful and erroneous responses, we asked whether children used the same or different geometric information to locate the targets in the depicted scene and on the depicted object.

Methods

Participants

Forty-eight 4-year-old children (22 females; mean age 4;6, range 4;0–4;11) saw pictures of an indoor scene and a table-top object. They were tested on their ability to interpret line drawings (N = 24) or photographs (N = 24) in these two contexts.

Design

Children were randomly assigned to view pictures of either type. Picture type (line drawings versus photographs) was a between-participants variable, with identical task instructions used for both types. Context (scene or object) varied within participants, with the order of the two contexts counterbalanced across children. In each context, children received six test trials with pictures presenting different views of the scene or object while they faced one of four directions relative to the scene or object. Fig. 2.1 shows the complete set of line drawings and photographs presented to children. The order of these trials and children's facing direction when viewing each picture were counterbalanced randomly across participants.

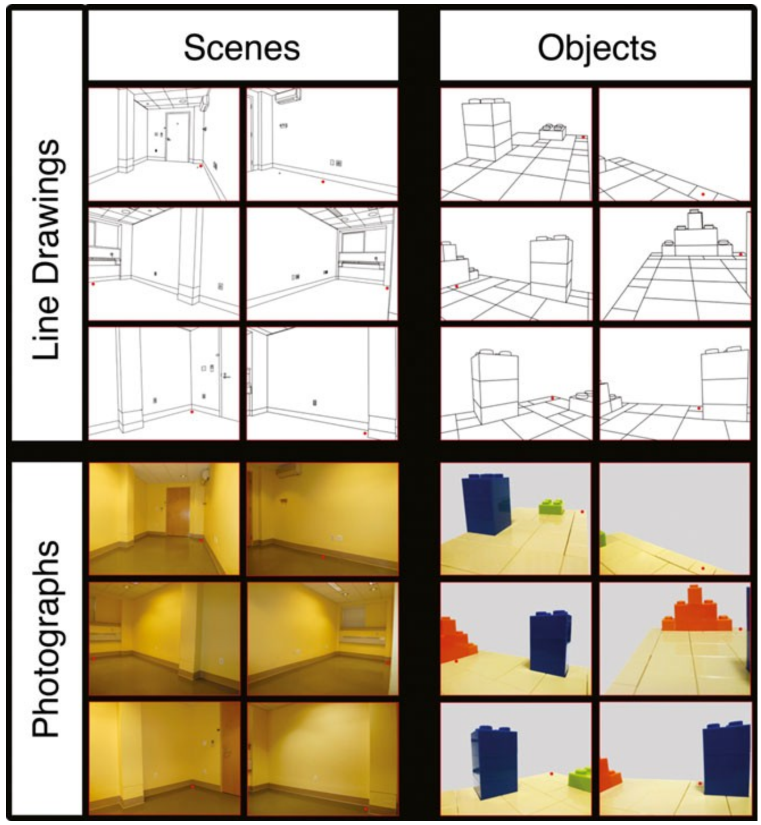

Fig. 2.1. Line drawings and photographs used in Experiment 1. Pictures of scenes and objects were designed to be as structurally similar as possible. In the line drawings, lines demarcated changes in contour, superposition, and perspective, but not changes in brightness.

Displays and procedure

In the scene context, the experimenter and participant entered a 5.44m x 2.51m lab testing room, which had been emptied of furniture but had a door on one short wall, a window on the opposite short wall, and a large column against one long wall. Six color photographs were taken of the room from six perspectives 97 cm off the ground (the height of a typical 4-year-old child). Six line drawings were created by tracing the edges of surfaces within each photograph. A single red dot was added to each picture to indicate the target location. There were six different test trials (and target locations) per condition and 10 possible response locations, indicated by red disks on the floor. Three of these six targets were located in the corners of the room, and the other three targets were located at or near landmarks in the room. Each target was defined by a unique combination of geometric and landmark relations, such that 100% correct responding was theoretically possible. Fig. 2.2 shows an overhead schematic of the targets and response locations.

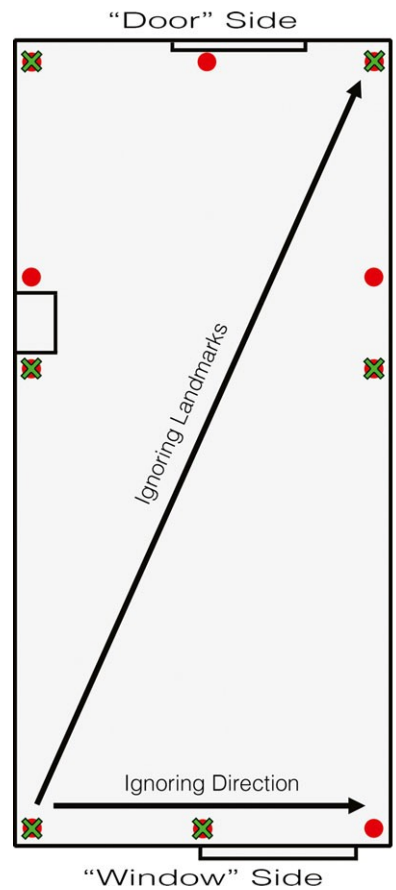

Fig. 2.2. Overhead schematic of the target (x) and non-target locations used in both the scene and object contexts in Experiment 1. Six target locations and 10 possible response locations allowed for precise classification of successful and erroneous responses. If children ignored landmark information, then they might have confused the corner by the door with the geometrically equivalent corner by the window. Moreover, if children ignored directional information, then they might have confused the corners to the left and to the right of the window. Error classification in the object context resembled that of the scene context but occurred with reference to the corresponding sides and landmarks of the Lego object.

On each trial, the child and the experimenter stood in the center of the room where the experimenter (who looked only at the picture or the child until the child completed the object placement) showed the child one of the line drawings or photographs, pointed to the target location on that picture marked by the dot, and asked the child to place a toy at that location in the room. Before the test trials, the child was acclimated to the room by standing at its center and turning around to point to each wall. Then, two practice trials were presented that used color rather than geometry to specify a target location. Children's responses were recorded for each test trial.

For the object context, a 5.5cm x 11cm x 2cm Lego object was built with three salient landmarks that were distinguished by shape and color. They were placed at locations corresponding to the locations at which the door, window, and column appeared in the room. Six color photographs of the object were taken to capture the same geometric and landmark information depicted in the scene context. Line drawings of the object were traced from these photographs. The object was affixed to a white rotating table (34.80cm in diameter), which was placed on top of a larger table in a lab testing room. Before the test trials, the child was acclimated to the object by turning the rotating table so that each side of the object faced them once. Children were encouraged to turn the table during the test trials to get different views of the object. Before the test trials, two practice trials were presented that used color rather than geometry to specify a target location. Test trials used the same procedure as the scene context as well as corresponding perspectives, target locations, and response locations (indicated by 10 red spots on the Lego object). Children's responses were recorded for each test trial.

Response classification

If young children engage core abilities to navigate the environment and recognize objects when interpreting pictures, then they should be just as successful when targets are located at the junctions of extended surfaces in the environment as when they are located near objects in both contexts. However, if children's responses depend on the context in which a picture is presented (i.e. whether the picture depicts a scene or an object), then they should rely more on the distances and directions of the extended surface layout when interpreting pictures of scenes and more on the local landmark features when interpreting pictures of objects. In the latter case, children would succeed more often in the scene context when targets are located at the junction of extended surfaces, and they would succeed more often in the object context when targets are located at or near objects. To test these possibilities, we compared the proportion of children's correct responses at the three corner targets and three landmark targets in the room or on the object. In addition, if children rely equally on extended surface information and object shape information in both contexts, then their placement errors should not differ across the two contexts. Alternatively, if children rely more on extended surface information in the scene context and on object shape information in the object context, then they should make more placement errors by ignoring 2D shape information in the scene context and more errors by ignoring directional information in the object context. To test these possibilities, we classified and analyzed children's error responses. Landmark errors were consistent with the relative distance and directional relations between the two walls of the room but inconsistent with the local landmark or surface information in the room, which would distinguish, for example, the corner by the door from the diagonally opposite corner by the window. Direction errors, on the other hand, were consistent with landmark information but not with the distance or directional relations that would distinguish, for example, a target to the left of the window with one to its right (Fig. 2.2). Error classification in the object context resembled that of the scene context but occurred with reference to the corresponding sides and landmarks of the Lego object. Because of the geometric structure of the room and of the object, the number of possible landmark and direction errors was not equal: There were five ways to make landmark errors (i.e. going to the diagonally opposite corner), but nine ways to make direction errors (i.e. going to the left or right of a target at a landmark). Children's error scores therefore were normalized by the total number of possible errors in each category.

Results

Initial analyses evaluated children's correct responding across all six trial locations. No performance differences emerged between male and female children [scene context: $t(46) = 0.09$, $P = .93$; object context: $t(46) = 0.67$, $P = .51$] or between children who viewed pictures in the scene and object contexts in different orders [scene context: $t(46) = 0.22$, $P = .83$; object context: $t(46) = 0.83$, $P = .41$]. Children tended to perform better with photographs than with line drawings, but this difference was not significant in either the scene context [$t(46) = 1.57$, $P = .12$] or the object context [$t(40.39) = 1.47$, $P = .15$]. Responses were collapsed across gender, order of contexts, and picture type for all further analyses.

We used a within-participants ANOVA to evaluate whether children's success at the targets located at either the corners or the landmarks of the room or object differed based on the context in which the pictures were presented. We found no significant effect of Context [$F(1, 47) = 0.06$, $P = .80$] or Target Location [$F(1, 47) = 0.01$, $P = .92$], indicating that overall success did not differ in either context or at either type of target location. However, we did find a significant Context x Target Location interaction [$F(1, 47) = 16.78$, $P < .001$; Fig. 2.3*A*], indicating that children's success at different target locations depended on the context in which the picture was presented. Direct comparisons of children's successful responding across contexts revealed that children performed significantly better at corner target locations in the scene context [$t(47) = 3.22$, $P < .01$] and at landmark target locations in the object context [$t(47) = 2.69$, $P = .010$]. These results are inconsistent with the hypothesis that pictures facilitate representations of scenes and objects that rely equally on extended surface and landmark shape information. Instead, they are consistent with past findings that young children rely selectively on different geometric information when using overhead maps to find targets located either at the midpoint of extended surfaces in the environment or at landmarks in that environment (Huang & Spelke, 2015). Children succeeded on almost half of the trials in each context [.47 responses], performing well above chance [Ps < .001]. However, children also made a large proportion of landmark and direction errors [.31]. The remaining errors not classifiable by our criteria [.22] were distributed across the remaining response locations [$M = .03$, $\sigma^2 < 8.6\ 9\ 10^{-4}$] with no apparent patterns.

Using a within-participants ANOVA, we tested the relative frequencies with which children ignored landmarks or ignored direction across the scene and object contexts. We found no significant effect of Context [$F(1, 47) = 0.05$, $P = .83$] or Error Type [$F(1, 47) = 2.07$, $P = .16$], indicating that overall error rates did not differ across contexts and that neither error type was more prominent. However, we did find a significant Context x Error Type interaction [$F(1, 47) = 7.74$, $P = .01$; Fig. 2.3*B*]. Direct comparisons of children's error patterns across contexts revealed that children made significantly more direction errors in the object context [$t(47) = 3.22$, $P < .01$] and marginally more landmark errors in the scene context [$t(47) = 1.84$, $P = .07$]. These results provide no evidence that children analyze pictures of scenes and objects in an integrated fashion. Instead, they are consistent with past findings that young children make errors by failing to integrate core geometric relations in tests of abstract geometric intuitions (Dillon & Spelke, in revision; Izard et al., 2011b) and in understanding of overhead maps (Dillon et al., 2013). Children in the present study produced both successful and erroneous responses that appeared to favor the distance and directional relations used for navigation when interpreting perspectival pictures of a 3D navigable layout or the shape relations used for form analysis when interpreting perspectival pictures of a 3D object.

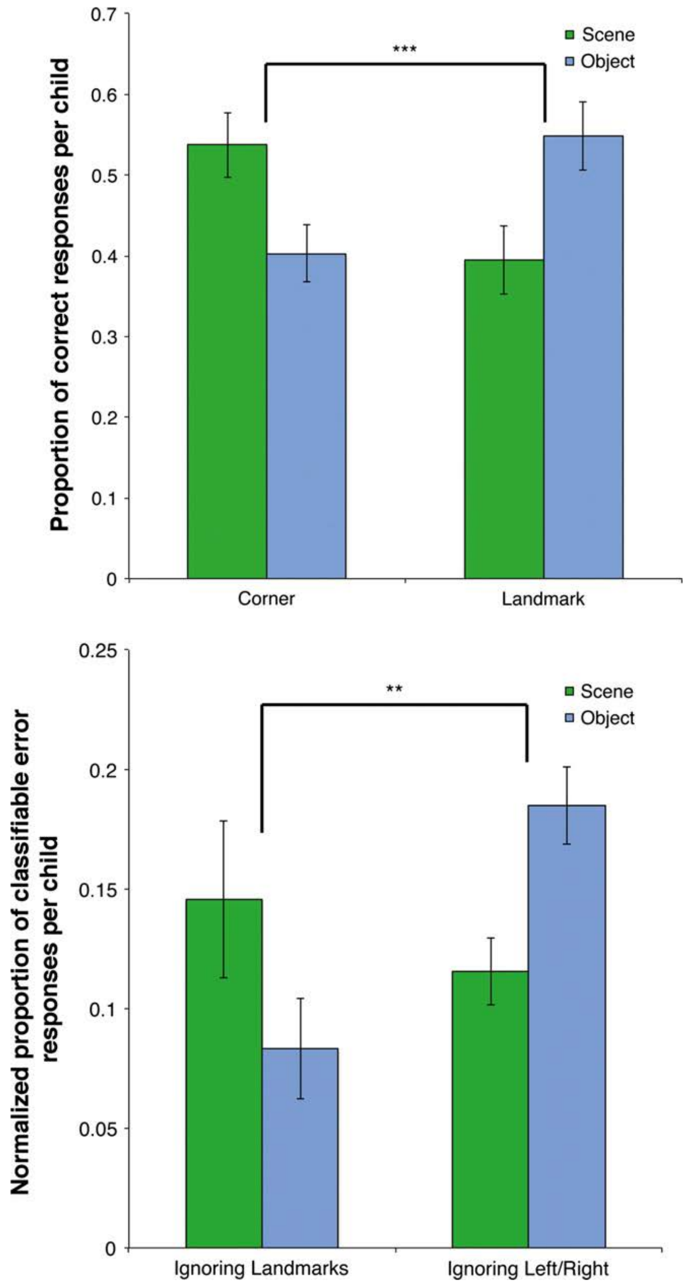

Fig. 2.3. (*A*) Proportion of correct responses at targets located at the junction of extended surfaces (corners) or at landmarks. Children were more successful at corner targets in the scene context and landmark targets in the object context. (*B*) Children's error responses also varied across the two contexts, with relatively more errors where they ignored landmarks in the scene context and relatively more errors where they ignored direction in the object context.

One additional analysis of the findings from Experiment 1 aimed to elucidate whether children's ability to interpret pictures of scenes and objects relied on any common information across the two contexts. If children extracted shared geometric information from pictures of scenes and pictures of objects, then children who performed better with pictures of scenes should have also tended to perform better with pictures of objects. A bivariate correlation, however, revealed no significant association between children's ability to interpret pictures of scenes and objects [$r(46) = .14$, $P = .35$]. These results thus suggest that children's interpretation of pictures not only is rooted in their sensitivity to geometric information rather than in some more general cognitive ability but also relies on different geometric information in different contexts.

Discussion

Although photographs offer color and texture cues missing from line drawings, children interpreted photographs and line drawings of scenes and objects at similar levels of performance, as in previous studies with adults and infants (Biederman & Ju, 1988; Shinskey & Jachens, 2014; DeLoache et al., 1979; Walther et al., 2011). Thus line drawings, which depict contour, superposition, and perspective, provided children with enough structural and geometric information about the 3D world to allow them to find targets without the addition of surface color or texture.

Children in the present study succeeded in relating different geometric information from two separate core systems to spatial symbols of high visual fidelity. Nevertheless, children's patterns of responding reflected limitations similar to what has been observed in children's interpretation of overhead maps: They relied on extended surface information when interpreting pictures of scenes, and landmark shape information when interpreting pictures of objects. If children had used the shapes of landmarks to find locations in the scene context, then they would have had equal success at corner and landmark targets and would have consistently distinguished between geometrically congruent locations, avoiding landmark errors. Similarly, if children had used distance and directional relations to find locations in the object context, then they would have had equal success at corner and landmark targets and would have distinguished between locations to the left and right of a landmark, avoiding direction errors. This pattern of results is further surprising given that the room landmarks were both more permanent and potentially more salient than the Lego landmarks: Children have names for the room landmarks (e.g. door, window, etc.), and walked through one of the landmarks to get into the room, whereas they have no distinctive names for the Lego pieces that composed each landmark, and they were not required to act on any of these landmarks. Indeed, because Lego pieces can be reconfigured, the pieces that served as landmarks in the object have no enduring existence or function.

Children's above-chance performance in the two contexts despite these errors presents two possibilities. First, children may have succeeded by sometimes relying on representations of landmarks in the scene context and representations of direction in the object context, indicating that they were partially but not completely integrating geometric information in both contexts. However, since the room and object were not perfectly symmetrical and included multiple features, children's success may have still depended only on one core system in each case. In particular, one long wall of the room contained a large protuberance like those children can use for navigation (Lee & Spelke, 2010). This feature would have allowed children to distinguish between targets at the two opposite corners of the room by encoding the contrasting distances and directions from that protuberance rather than from a landmark object. Similarly, the object contained multiple landmarks, allowing children to encode a target as located between two such landmarks rather than to the left or right of just one. The present analysis does not distinguish between these possibilities or reveal whether children have some capacity, albeit an imperfect one, for integrating geo- metric information across the two core systems. Experiment 2 begins to address this question by using an individual differences approach to test for interrelations between children's core systems of geometry dedicated to navigation and object recognition and their interpretation of perspectival line drawings of scenes. This approach allows us to test the prediction that children's interpretation of line drawings can be significantly explained by one or both of their core geometric sensitivities.

Experiment 2

Experiment 2 was conducted on 4-year-old children who had also participated in a separate study of navigation, visual form analysis, and map interpretation (Dillon et al., 2013). In the present experiment, children were given a line drawing interpretation task depicting scenes, similar to that of the scene context in Experiment 1. Their performance on this task was then compared to their performance on the tests of reorientation and visual form analysis that were conducted for the other study (Dillon et al., 2013). Using hierarchical regression analyses, we evaluated whether children's performance on the reorientation and form analysis tasks predicted their interpretation of the line drawings of scenes, after controlling for age and verbal ability. If the response patterns in the scene context of Experiment 1 indeed depended on children's recruitment of the geometric information they use to navigate, then children who recruit this system more effectively in a non-symbolic reorientation task should be better able to interpret line drawings of scenes. In addition, if children recruit the geometric information they use to analyze visual forms (at least partially) to interpret drawings of scenes, then those children who perform better on a non-symbolic test of visual form analysis should also perform better on the line drawing interpretation task depicting scenes.

Methods

Participants

Forty-five 4-year-old children (23 females; mean age 4;6, range 4;0–4;11) visited the lab to participate in two testing sessions for a study of map interpretation (Dillon et al., 2013). All these children also completed the line drawing interpretation task in Experiment 2.

Design, procedure, and analyses

Children were asked to use perspectival line drawings to locate targets in a depicted lab testing room, which had been emptied of furniture (as in the scene context of Experiment 1). Because Experiment 2 aimed to test for relations between non-symbolic and symbolic uses of geometry, but not to examine response patterns, the task was designed so that children could achieve higher levels of performance than in Experiment 1. Five trials with five possible response locations were included, counterbalancing the picture-presentation direction with the restriction that the target was never entirely out of view behind the child.

Children in the present experiment also participated in the experiment of Dillon et al. (2013), which consisted of four tasks conducted over two visits to the lab. Three of these tasks contributed data to the present analyses and are therefore described here (see Dillon et al., 2013, for a full description of these tasks). In one visit, children completed two non-symbolic tasks used to elicit core geometric representations in young children and animals. The first was a navigation task in which children were disoriented within two rectangular environments with different aspect ratios and then were allowed to reorient by the shape of each environment to locate a hidden object. The second was a visual form analysis task in which children were presented with a succession of nine visual arrays displaying five similar shapes and one shape-deviant that differed in either proportional length, angle size, global shape, or relations of parallelism and alignment. Children were asked to pick out the form that did not belong with the rest. On a different visit, children completed the Peabody Picture Vocabulary Test (PPVT), a measure of verbal intelligence (Dunn & Dunn, 1997), which followed the line drawing interpretation task described above. Twenty-three children completed the set of non-symbolic tasks on their first visit followed by the line drawing and verbal task on their second visit, and 22 children completed these sets of tasks in the opposite order. To determine if and how the different geometric relations used in navigation and visual form analysis related to children's interpretation of line drawings of scenes, we conducted regression analyses based on children's average scores across conditions that yielded above-chance performance.[3]

Results

No performance differences were found between male and female children on the line drawing task [$t(43) = 1.25$, $P = .22$] or between children who completed the line drawing task on their first or second visit [$t(43) = 0.27$, $P = .79$]. These findings accord with those of Dillon et al. (2013), who found no gender or order effects in the other geometric tasks. Finally, children performed above chance [0.2] on the line drawing task [$t(44) = 12.03$, $P < .001$].

[3]Children participating in Dillon et al. (2013) navigated three rectangular enclosures of different aspect ratios. However, children showed above-chance performance in only two of these enclosures. As a result, children's performance in the least-elongated enclosure was not included in the analyses of that experiment or in the present experiment. Dillon et al. (2013) also presented children with a total of 16 visual form analysis trials, nine of which elicited above-chance performance. These nine trials were included in the analyses of Dillon et al. (2013) and in the analyses for the present experiment.

Regression analysis

Children exhibited appropriately distributed variability in their responses in the line drawing task ($M = .69$, $\sigma^2 = 0.08$) as well as in the other three tasks considered in the present analyses (see Dillon et al., 2013; Chapman & Chapman, 1978). As confirmation that parametric tests were appropriate for these data, the approximate normality of regression residuals was confirmed by comparison to the standard bell curve and examination of QQ-plots.

Age was a significant predictor of children's performance on the line drawing interpretation task [β(Age) = 0.36; $P = .02$], but children's verbal abilities were not [β(PPVT) = 0.20; $P = .17$]. After controlling for both of these variables, children's performance on the line drawing interpretation task was predicted by their use of distance and direction on the reorientation task [β(Reorientation) = 0.28; $P = .05$; Fig. 2.4] but not by their use of relative length, angle, and global shape on the visual form analysis task [β(VFA) = 0.05; $P = .74$].

These results are inconsistent with the hypothesis that children's interpretation of line drawings relies on an integrated representation of the geometry dedicated to navigation and object recognition: Children relied on the geometric information used for navigating 3D environments – the distances and directions of extended surfaces in an indoor scene – but not the geometric information used for recognizing object shapes to analyze the 3D information represented in the 2D line drawings of scenes. As a result, children's interpretations of line drawings of scenes appear to be consistent with previous findings testing young children's understanding of over- head maps, which find limited reliance on the geometric information used for navigation or object recognition based on context.

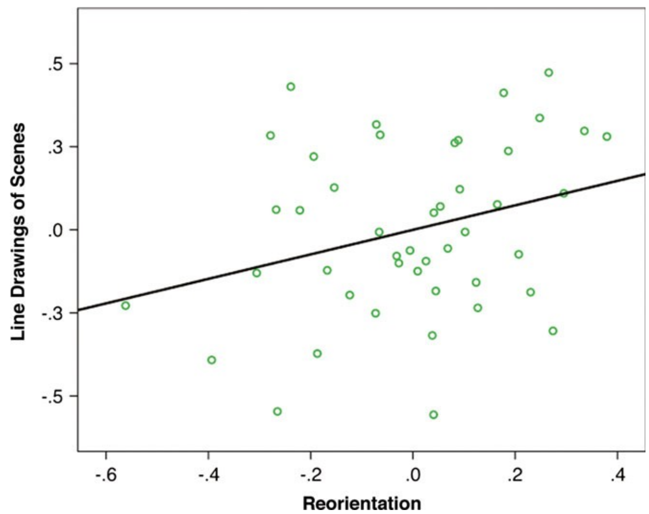

Fig. 2.4. Experiment 2: Partial regression plot showing the relation between children's scores on the reorientation task and the line drawing interpretation task depicting scenes, after controlling for age and verbal intelligence.

Discussion

The findings of Experiment 2 provide further evidence that children recruit representations guiding navigation but not object shape analysis to interpret line drawings of scenes. Even though the line drawings in Experiment 2 consisted of a collection of 2D shapes on a 2D surface and presented scenes from familiar viewpoints, children showed no evidence of recruiting representations supporting the analysis of visual forms. The reasons for these findings are unclear. First, it is possible that children selectively recruit the geometric representations used to recognize object shapes when analyzing drawings of objects but not scenes, as suggested by the findings from Experiment 1 and by previous work on overhead maps. Thus, children's performance on a form analysis task may not relate to their performance when interpreting line drawings of scenes because the two tasks depend on different geometric information. Alternatively, the visual form analysis task used in Experiment 2 simply may not capture meaningful variation in children's sensitivity to geometric shape properties when such properties are presented in perspectival pictures. Experiment 3 addressed these possibilities by testing whether children's performance on the same visual form analysis task was related to their interpretation of line drawings of objects, as suggested by the findings of Experiment 1 and as predicted by the thesis that children extract different geometric information from pictures of scenes and pictures of objects.

Experiment 3

Experiment 3 used an individual differences method similar to that of Experiment 2, but abbreviated to a single session and with a smaller group of children. The test of verbal intelligence was eliminated since it did not capture any significant variation in children's line drawing interpretation in Experiment 2. Children in Experiment 3 performed the same line drawing interpretation task as in the object context of Experiment 1 and the same test of visual form analysis that was entered into the analysis of Experiment 2. We asked whether performance on the form analysis task predicted performance on the line drawing task depicting objects, even though it did not predict performance on the line drawing task depicting scenes. If children rely only on the geometric information used for navigation to interpret all perspectival line drawings or if the visual form analysis task fails to capture children's sensitivity to object shape properties in perspectival drawings, then, as in Experiment 2, there should be no relation between children's performance on the visual form analysis task and their performance on the line drawing task depicting objects. However, if children recruit different geometric representations for analyzing drawings of scenes versus objects, then those who excel at analyzing the shapes of visual forms might also excel at interpreting the 2D shapes in line drawings of objects.

Methods

Twenty-four 4-year-old children (11 females; mean age 4;6, range 4;0–4;11) participated in this experiment. One additional child was excluded from the analysis due to a failure to follow the task directions.

Children interpreted line drawings from the object context of Experiment 1 and were measured on their ability to analyze visual forms based on length, angle, global shape, and alignment relations. The visual form analysis task was the same task used in Experiment 2, which was based on that of Dillon et al. (2013) and consisted of the nine items from that task on which children showed above-chance performance. Twelve children completed the line drawing interpretation task first followed by the visual form analysis task, and 12 children completed these tasks in the opposite order.

Results

We found no performance differences between male and female children on either of the tasks [line drawings: $t(22) = 0.68$, $P = .50$; visual form analysis: $t(22) = 0.89$, $P = .38$] and no performance differences between children who completed the line drawing task first and those who completed the visual form analysis task first [line drawings: $t(22) = -0.36$, $P = .72$; visual form analysis: $t(22) = -0.68$, $P = .50$].

Children performed above chance on the form analysis task [$t(23) = 6.82$, $P < .001$], consistent with past research using this task with children and adults (Dehaene et al., 2006; Dillon et al., 2013). Children also performed above chance on the line drawing task depicting objects [$t(23) = 6.24$, $P < .001$]. These data met the specifications for use in regression analyses as described above [visual form analysis: $M = .54$, $\sigma^2 = 0.07$; line drawings: $M = .45$, $\sigma^2 = 0.08$]. Age was not a significant predictor of children's performance on the line drawing task [$\beta(\text{Age}) = 0.03$; $P = .87$], but critically, performance on the line drawing and visual form analysis tasks was systematically related: After controlling for age, children's visual form analysis scores predicted their performance on the line drawing task depicting objects [$\beta(\text{VFA}) = 0.54$; $P = .02$; Fig. 2.5).

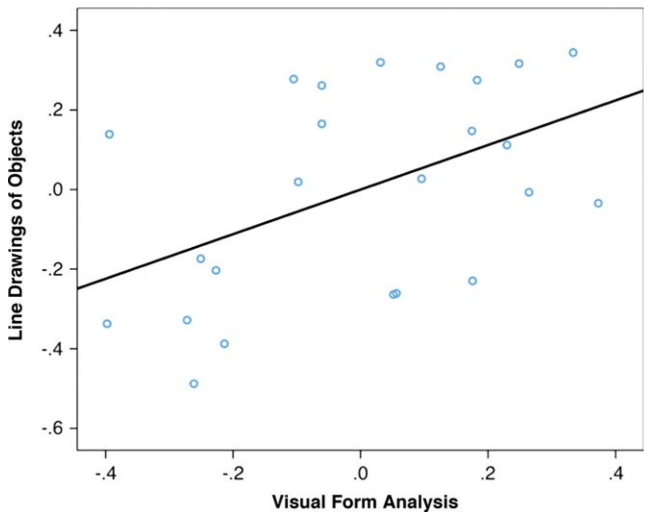

Fig. 2.5. Experiment 3: Partial regression plot showing the relation between children's scores on the visual form analysis task and their scores on the line drawing task depicting objects, after controlling for age.

Discussion

Although children's ability to analyze visual forms was not related to their ability to interpret line drawings of scenes in Experiment 2, it was related to their ability to interpret line drawings of objects in Experiment 3. Together with the findings of Experiment 2, the present findings thus suggest that children's failure to recruit the geometric information used for object shape analysis in Experiment 2 was not due to a failure in the non-symbolic shape analysis task to capture any meaningful variation in children's interpretation of perspectival pictures. Instead, these results reveal that children's interpretation of perspectival pictures that present familiar points of view is similar to their interpretation of overhead maps: Children flexibly interpret perspectival line drawings by recruiting the non-symbolic geometric information used for navigation or object recognition based on context.

General Discussion

Together, the findings from these three experiments suggest that children are flexible in using distance and directional information as well as object shape information to interpret perspectival line drawings, but limited in their ability to combine this information to achieve integrated geometric representations of scenes and objects. Such flexibility and limitations are similar to those observed in children's interpretation of overhead maps. This conclusion depends on three main findings. First, 4-year-old children interpret pictures of scenes by relying on the same geometric relations of distance and direction that guide their navigation through extended surface layouts. Second, 4-year-old children interpret pictures of objects by relying on the same shape information that guides their recognition of objects and small-scale visual forms. Third, 4-year-old children show no evidence of integrating the geometric information for navigation and object shape analysis from their two core systems. We discuss each conclusion in turn and describe how together they might begin to elucidate the developmental foundations of symbolic and abstract geometric understanding.

Core geometry for navigation guides children's interpretations of depicted scenes

When interpreting pictures of scenes, children in Experiment 1 exhibited key signatures of relying on the same geometric information they use to navigate the environment. Specifically, children relied on distance and directional information to find either the correct targets or targets at diagonally opposite locations in the room, and they erred by ignoring the shapes of surface markings and landmarks, as they do during other symbolic (Dillon et al., 2013; Huang & Spelke, 2013) as well as non-symbolic navigation tasks (see Cheng & Newcombe, 2005; Cheng, Huttenlocher & Newcombe, 2013; Spelke & Lee, 2012). In Experiment 2, children's ability to interpret line drawings of scenes was predicted by their performance on a non-symbolic navigation task but not by their performance on a non-symbolic form analysis task. Findings from both experiments thus provide evidence that children use common geometric information to navigate their environment without spatial symbols and with spatial symbols of varying points of view and levels of detail.

This finding is striking for two reasons. First, because line drawings of scenes depict 2D visual forms on a 2D surface, one might have expected children to interpret them by recruiting the geometric sensitivities used to analyze 2D visual forms. Contrary to this expectation, children interpreted the 2D small-scale pictures of scenes using the same geometry as they would to interpret the 3D navigable layouts themselves. Nevertheless, children succeeded in using the 2D forms to analyze the 3D layout, an achievement not found in purely non-symbolic navigation tasks (Huttenlocher & Lourenco, 2007; Lee & Spelke, 2011; Lee et al., 2012a; Lourenco et al., 2009). Second, because perspectival line drawings depict their referent from familiar points of view, one might have expected that children would more easily extract from them geometric information relevant to both navigation and object shape analysis. However, children appear just as limited in using integrated geometric information in these pictures as they do in pictures presenting unusual viewpoints such as overhead maps. As is the case with overhead maps, the referent of the line drawing, not the properties of the drawing itself, appear to guide children's interpretation of their geometry.

Core geometry for form analysis guides children's interpretation of depicted objects

When interpreting pictures of objects, children in Experiment 1 exhibited key signatures of relying on the same geometric information they use to recognize object shapes. Specifically, children relied on relative length and angle relations defining the shapes of landmarks to choose either the correct targets or the incorrect targets located near, but on the wrong side of, the object's parts. In making these errors, children ignored directional information as they do during non-symbolic form analysis tasks, in which children and adults often confuse objects and forms with their mirror images (Gregory & McCloskey, 2010; Dehaene et al., 2006). In Experiment 3, children's ability to interpret line drawings of objects was predicted by their performance on a non-symbolic form analysis task. These findings provide evidence that children use common geometric information to recognize the shapes of objects with or without spatial symbols.

Experiments 1 and 3 further suggest that children do not directly engage non-symbolic geometric information for navigation when interpreting perspectival line drawings of objects, even when such drawings capture the spatial structure of scenes. Neuroimaging studies targeting the parahippocampal place area (PPA) show that this brain region responds to global scene structure, including ‘Lego scenes’ that look very much like those tested in the object conditions of Experiments 1 and 3 (Epstein, Harris, Stanley & Kanwisher, 1999). Though such Lego scenes activate cognitive systems dedicated to scene recognition, they may nevertheless engage geometric representations dedicated to object recognition when such Lego scenes indicate a Lego object, as they do in Experiments 1 and 3. The flexibility children displayed in interpreting the scene-like pictures of the Lego object, relative to the Lego object itself, suggests that a drawing’s symbolic meaning affects the geometric information recruited for its interpretation. Thus, one extension of the present work would be to analyze children’s interpretation of the very same drawings of the same Lego structure both in the context of a large-scale Lego scene and also in the context of a small-scale Lego object.

These results are consistent with other findings that a highly realistic drawing or photograph may serve as a symbol for children, with the geometric elements of the picture remaining open to interpretation based on the context in which it is presented. Although young infants may attempt to perform actions on pictures that suggest confusion between the picture and its referent (DeLoache, Pierroutsakos & Uttal, 2003), these actions disappear in the second year of life and are replaced by acts of pointing and naming (DeLoache, Pierroutsakos, Uttal, Rosengren & Gottlieb, 1998). Moreover, when 18- and 24-month-old children were repeatedly presented with a novel word, ‘whisk’, applied to a line drawing of a whisk, they chose either the real object alone or the real object and the drawing when later asked for the ‘whisk’ (Preissler & Carey, 2004). This finding holds not only for highly iconic symbols, but also for more abstract spatial symbols such as overhead maps. Still, other symbolic representations may be entirely devoid of any iconicity, and it is unknown how this level of abstraction would manifest in children’s treatment of scenes and objects. For example, it is possible that children would interpret the relative heights on a bar graph identically regardless of whether they represented the relative distances between houses in a neighborhood or the relative positions of parts on an object (Friel, Curcio & Bright, 2001). To our knowledge, this possibility has not been tested.

Children show no evidence of integrating core geometric representations when interpreting perspectival pictures

Although children showed equal success in interpreting structurally similar 2D perspectival pictures of scenes and objects, we found no indication that they combined extended surface representations of distance and direction with small-scale shape representations of relative length and angle to find targets in the 3D layout. In Experiment 1 children extracted geometric information from pictures of both scenes and objects, but did not use this information in an integrated fashion. When interpreting pictures of scenes, children's successful and erroneous responses indicated that they relied on distance and directional information more than landmark shape information. When interpreting pictures of objects, in contrast, the same two measures indicated that children relied on landmark shape information more than directional information. This negative conclusion does not imply, however, that children are unable to effect such combinations when reading spatial symbols. The picture interpretation tasks used in the present studies invited, but did not require, such combinations. It is possible that children would show integration of these types of geometric information if they were given a task that required these combinations.

Nevertheless, the present findings are striking because previous work has shown an advantage of highly realistic pictures to encourage children to extract relevant information from symbolic representations in domains other than geometry (Ganea et al., 2008; Simcock and DeLoache, 2006). Despite that advantage, the present findings are consistent with previous evidence that young children fail to use the geometric relations of distance and angle in an integrated fashion when they navigate by spatial symbols such as overhead maps (Dillon et al., 2013) or perform more abstract triangle completion tasks (Dillon & Spelke, in review; Izard et al., 2011b). It is possible that children will begin to exhibit integrated geometric knowledge during picture interpretation when they also begin to show an integrated understanding of distance and angle in these other abstract geometry tasks. Alternatively, children may show more integrated knowledge when they confront pictures earlier than when they confront maps or verbal tests of abstract geometric intuitions, but this difference might not be apparent at age 4 years. For example, pictures may better foster the encoding of spatial expressions and object names in older children.

Conclusion: Core geometry in perspective

Understanding spatial symbols, such as maps and line drawings, is essential to functioning in our highly symbolic human culture. Such understanding requires the integration of information from two core systems of geometry, but this integration undergoes a protracted development that is not complete until adolescence (Dillon & Spelke, in review; Izard et al., 2011b). It is possible that children begin to exhibit integrated geometric knowledge during picture interpretation only when they begin to gain an integrated understanding of geometry in more abstract contexts. Alternatively, pictures may reveal children's first signs of integrating geometric information before maps and other more abstract geometric constructions do, but this change may begin after age 4.

The present findings suggest that pictures of all kinds serve as media in which children deploy different core geometric representations flexibly, and they therefore may offer children the opportunity to relate these representations to one another. Spatial symbols represent both 3D scenes and objects, joining the distance and directional information used to navigate with the relative length and angle information used to recognize objects by their shapes. If these suggestions are correct, cognitive scientists may elucidate the processes by which geometric abstractions arise by charting the development of children's engagement with the abstract geometric relations presented in pictures, perspectival art, and other spatial symbols. Further, if abstract geometric understanding builds on core mechanisms that emerge in infancy and are used throughout our lives, then efforts to enhance those capacities through education may benefit from a pedagogy that links the formal systems children must master to their everyday acts of navigation, object recognition, and pictorial interpretation. For example, training studies could investigate whether intense experience with spatial symbols affects the emergence and growth of abstract geometric intuitions. Continued research probing the mechanisms of change in spatial cognitive development, combining studies of navigation and object recognition with studies of pictorial perception and interpretation, may ultimately shed light on the uniquely but universally human geometric understanding at the foundation of science and mathematics.

Paper 3: Young children's use of surface and object information in drawings of everyday scenes

Dillon, M. R., & Spelke, E. S. (2016). Young children's use of surface and object information in drawings of everyday scenes. *Child Development*.

Spatial symbols, such as photographs, drawings, and maps, represent the distances, directions, lengths, and angles of both extended surface layouts and small-scale objects. Such symbols are meaningful to infants, young children, and adults from many cultures (Dehaene et al., 2006; DeLoache, 1987, 1991, 2004; Shinskey & Jachens, 2014; Winkler-Rhoades et al., 2013). Most studies of children's interpretation of spatial symbols have focused on their implicit understanding that pictures represent scenes and objects and thus cannot be moved through or acted upon (e.g., DeLoache, 2004; Preissler & Carey, 2004). However, recognizing that something is a symbol is only one step toward its use. Little is yet known about how children relate the geometry in pictures to the scenes and objects that these pictures represent. In this study, we ask what information children use and what information they think is useful when interpreting line drawings of a typical furnished room. We thus evaluate how symbol reading might engage those sensitivities that form the foundation both of our everyday interactions with the spatial world and of our more abstract geometric reasoning.

Human sensitivity to shape information in edge-based perspectival line drawings of scenes and objects is afforded by basic properties of our visual system. By capturing the occluding and non-occluding edges of the surfaces and objects in a scene, but not the brightness edges, such line drawings present the depicted world in a highly interpretable fashion (Cole et al., 2009; Gibson, 1971; Hubel & Weisel, 1962; Hubel & Wiesel, 1968; Kennedy & Ross, 1975; Olshausen & Field, 1996; Sayim & Cavanagh, 2011; von der Heydt et al., 1984). Although the capacity to recognize two-dimensional (2D) shape information in such drawings is present in the visual systems of other animals (Kirkpatrick-Steger, Wasserman, & Biederman, 1998), 1.5- to 2-year-old children go beyond detecting the basic similarities between pictures and their referents, and begin to view pictures as symbols that provide information about their referents (Preissler & Carey, 2004). Indeed, in a search paradigm pioneered by DeLoache (1987, 1991), 2.5-year-old children were able to retrieve a hidden doll in a room when given only a picture of its hiding location (DeLoache, 2004; see also Winkler- Rhoades et al., 2013; Uttal & Yuan, 2014).

Studies have begun to examine what geometric information children use when navigating by such spatial symbols. For example, 4-year-old children use the length relations defining locations in an environment when navigating by a symbolic map (Huttenlocher et al., 1999; Izard, O'Donnell, & Spelke, 2014) but not when navigating without a map (Lee et al., 2012a). Moreover, 4-year-old children use the relative sizes of angles to navigate by overhead maps specifying locations in a fragmented three-dimensional (3D) triangular environment in which only corner angles of different sizes are present (Dillon et al., 2013; Izard et al., 2014), but 2-year-old children ignore angle information when navigating without a map in a 3D fragmented rhomboidal environment (Hupbach & Nadel, 2005; Lee et al., 2012a). Four-year-old children extract and use distance and directional information in 2D forms when those forms are presented as symbolic drawings of a 3D room (Dillon & Spelke, 2015), but even older children often fail to use directional information when differentiating between non-symbolic 2D visual forms and their mirror images over changes in orientation (Dehaene et al., 2006; Izard & Spelke, 2009).

Spatial symbols thus permit children to access geometric information more flexibly than they otherwise would when navigating environments or recognizing objects without symbols.

Despite this flexibility, young children's use of spatial symbols suffers from serious limitations when compared to that of adults. For example, Dillon and Spelke (2015) investigated 4-year-old children's use of geometry when interpreting highly realistic perspectival line drawings and photographs of an empty 3D room and a 3D Lego object with the same metric and landmark properties as the room. Despite being presented with canonical viewpoints in the pictures, children interpreted pictures using different geometric information depending on whether the pictures were presented in the context of the room or the object. In the former case, children recruited representations of absolute distance and direction used for navigation, and in the latter case, they recruited representations of relative length and angle used for shape analysis. With the pictures of the room, children located targets more successfully at corners, and they erred by ignoring the shapes of surface markings and landmarks. With the pictures of the object, in contrast, children located targets more successfully near landmarks, and they erred by ignoring the directional relations that differentiated a target to the left of a landmark from one to its right. In addition, children's picture-guided search of the room was predicted by their scores on a non-symbolic navigation task, whereas their picture-guided search of the object was predicted by their scores on a non-symbolic shape analysis task. Similar findings were obtained in experiments in which children navigated by overhead maps (e.g., Dillon et al., 2013; Huang & Spelke, 2015): With maps as with perspectival pictures, children flexibly extracted geometric information from the spatial symbols, but they used only one set of geometric representations at a time, either those relevant to navigating through a scene or those relevant to recognizing objects, depending on the context in which the symbols were presented.

Can young children nevertheless use spatial symbols to relate large extended surfaces to small-scale landmark objects during a search task? Surfaces and objects occur together in scenes and in pictures of scenes, but their shape properties are encoded by distinct regions of the brain (e.g., Doeller et al., 2008), and they are dissociated behaviorally in preschool-aged children and non-human animals (e.g., Cheng, 1986; Hermer & Spelke, 1996). A series of studies on adults' and children's navigation without symbols has shown that there is at least one uniquely human capacity that is effective at promoting the integration of surface and object information: language. Adults are thought to engage linguistic processes when they spontaneously combine geometric properties of the extended surface layout with landmarks, that is, when they reorient themselves in a room with one wall that is a different color from the others or has an object in front of it. Integrating surface geometry with landmark information during this search task emerges at about 6 years of age, correlates with the use of the words "left" and "right" during referential communication (Hermer-Vazquez, Moffet, & Munkholm, 2001) and declines in adults during a verbal shadowing task (Hermer-Vazquez, Spelke, & Katsnelson, 1999) unless adults are alerted to its relevance (Ratliff & Newcombe, 2008). Finally, even 4-year-old children can distinguish targets using the combination of extended surface geometry and landmarks when language is used to highlight the relevant landmark information (e.g., "I'm hiding the sticker at the colored wall"; Shusterman, Lee, & Spelke, 2011).

These findings raise the question of whether non-linguistic spatial symbols, such as maps or pictures, would also lead 4-year-old children to relate extended surface information to landmark objects when they navigate. Previous studies investigating this question found no evidence for this ability (as described above), but those studies presented children with pictures depicting the world from an unfamiliar perspective (e.g., an overhead view in a map) or depicting an unusual environment or object (e.g., a fragmented or empty room, or an arbitrarily constructed Lego object). In contrast, children interact with the world from their eye-level perspective rather than from above, and these perspectives typically incorporate information about both extended surfaces and objects. Preschool children are more successful at finding the geometric correspondences between maps and environments when the environments are familiar and are presented from a familiar perspective (Liben & Yekel, 1996). In creating their own maps, moreover, children in kindergarten tend to use eye-level perspectives, whereas older children tend to adopt overhead views (Liben & Downs, 1994). Even adults are better at interpreting line drawings and photographs that present objects from familiar, canonical viewpoints (Tarr & Pinker, 1989; see also Landau et al., 2006), suggesting that visual experience plays a role in extracting relevant shape properties from drawings.

Children might also form more integrated interpretations of pictures depicting surfaces and objects from familiar perspectives because the pictures that they typically encounter, for example, in story- books, often include both surface and object information together. A survey of prize-winning children's books (winners of the Caldecott Medal, given each year by the American Library Association to the illustrator of the most distinguished picture book for children) revealed that the vast majority of pictures in these books (90.3%) depict both surfaces and objects together, whereas only 2.5% of pictures include just surface information, and only 7.2% of pictures include just object information (see Supporting Information for more information). Preschool children might build on their experiences with such pictures to form more integrated representations of the scenes that they depict.

Children's typical interactions with canonical scenes and pictures of surface layouts and objects together, presenting perceptually familiar view-points with high fidelity, may therefore elicit better performance in a symbolic spatial task (Callaghan, 2000; Ganea et al., 2008; Simcock & DeLoache, 2006, 2008; Uttal & Yuan, 2014; Walker, Walker, & Ganea, 2013) and provide evidence for a more integrated understanding of layout and object geometry than has been observed in previous studies. To investigate this possibility, we compared children's ability to find locations in a room using information in three different types of drawings: drawings depicting only a room's extended surfaces, drawings depicting only the objects in the room, and drawings depicting the room's surfaces and objects together, all with realistic renderings of occlusion. If children can integrate information about surfaces and objects in drawings, then they should show enhanced abilities to interpret pictures displaying both the extended surface layout and the objects in that layout.

Finally, although prior studies have shown children's flexible use of geometry when reading spatial symbols, no studies have explored children's awareness of the geometric properties of pictures that make them informative representations of scenes. When looking at a picture of a room, children might recognize that extended surface information is more informative about locations that are specified by the extended surfaces in the 3D layout and that landmark shape information is more informative about the locations in the room near landmark features. Children might then selectively attend to the relevant information in the symbol or in the environment to complete the picture-interpretation task.

Alternatively, children might extract geometric information from spatial symbols automatically whenever these symbols are presented in a particular 3D context and without any awareness of the information that they are using. When a drawing is meant to represent an extended surface layout, for example, children might automatically extract the distance and directional information that guides their navigation in such a layout; when a drawing represents one or more objects, children might automatically extract the relative length and angle information that guides object recognition and categorization. Such automatic responses have been observed in adults' use of shape information in everyday non-symbolic acts of navigation and object recognition (e.g., Doeller et al., 2008).

In order to investigate young children's sensitivity to the geometry of extended surface layouts and the objects in those layouts when interpreting pictures, we asked 4-year-old children to locate target disks in a room using line drawings of that room (Experiment 1) and to evaluate which of two line drawings better indicated a specific target location (Experiment 2). In both experiments, we manipulated the information in the drawings, showing children either extended surface information only, object information only, or (in Experiment 1) both surface and object information together. We also manipulated the location of the target, which was either in a corner of the depicted room or near an object in the room. First, we evaluated whether children performed better when given pictures that had both extended surface information and object information together, compared to just the one type of information that better specified each target location. Then, we evaluated whether children correctly judged which pictures would be most useful for finding different locations in the room.

General Methods

Displays

Both experiments took place in a 5.44m x 2.51m laboratory testing room, which had a door on one short wall, a window on the opposite short wall, and a large column against one long wall. The room was furnished with two stacking chairs, one swivel chair, one storage bin, one trashcan, and one child- sized table with two child-sized chairs. The two stacking chairs were the same model, but one was placed with its back to the long wall with the column, and the other was placed with its back to the short wall with the window. The storage bin and the trashcan had a similar shape, but the storage bin was bigger. The bin was placed to the left of the stacking chair by the window, and the trashcan was placed to the left of the stacking chair by the column. The child-sized table was placed toward the window side of the room with the matching chairs at its opposite corners. The swivel chair was placed in the corner or the room to the right of the door. This setup resulted in four objects located on the door side of the room and four objects located on the window side of the room (Fig. 3.1).

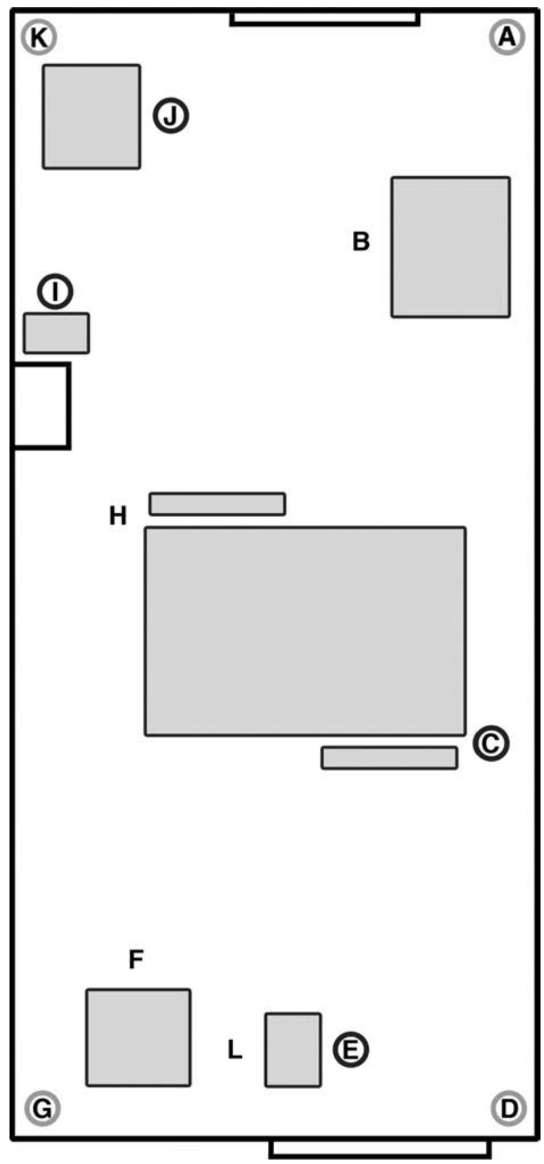

Fig. 3.1. Overhead schematic view of the room, objects, and target locations in the line drawing interpretation and evaluation tasks. The room is drawn to scale and the diagram indicates the location of the door (top) and window (bottom) on opposing walls. The column against the wall of the room is indicated on the left of the diagram by a white box with a black outline. Objects in the room are indicated by gray rectangular shapes. Possible response locations are labeled by letters (A–L). A light gray circle around a letter indicates that it served as a corner target, and a dark gray circle around a letter indicates that it served as an object target.

Twelve bright red rubber disks (10cm in diameter and 0.5cm in thickness; six on the door side of the room and six on the window side of the room) were placed on the floor to serve as possible response locations. The floor was gray, providing a strong contrast to the red disks, and there were no other red objects in the room. Eight of the response locations were used as targets in the experiments (four on the door side of the room and four on the window side of the room). Four targets were located at the room's corners (i.e., the junctions of the room's extended surfaces), and four targets were located next to objects in the room. Non-target disks were placed at locations in the room that bore similar relations to the room features (Fig. 3.1).

Eight color photographs were taken of the room from eight different perspectives, 97cm off the ground (the height of a typical 4-year-old child). Three sets of eight line drawings were created by tracing the edges of occluding and non-occluding surfaces in each photograph (Fig. 3.2). In the first set of drawings, only the lines indicating the room's extended surfaces were depicted, including its walls, floor, ceiling, outline of the door and window frames, and the wall-mounted air conditioner, all presented as complete lines as if the room contained no occluding objects. In the second set of drawings, only the lines indicating the shapes of the objects were depicted, all presented as complete lines except where one object was partly occluded by another. Although these two sets of drawings depicted the room from canonical viewpoints, their depiction of only limited information was likely highly unusual to children, as children's typical eye-level views often present extended surface and object information together, and the typical pictures that they encounter include both surface and object information together. The third set of drawings were thus designed to be not only accurate in their rendering of the room but also more familiar: Lines indicated the room's extended surfaces and its objects together, with accurate renderings of occlusion. A single red dot—indicating one of the target disks in the room and consistent across the corresponding drawings in the three sets—was added to each drawing to indicate the target location (Fig. 3.2).

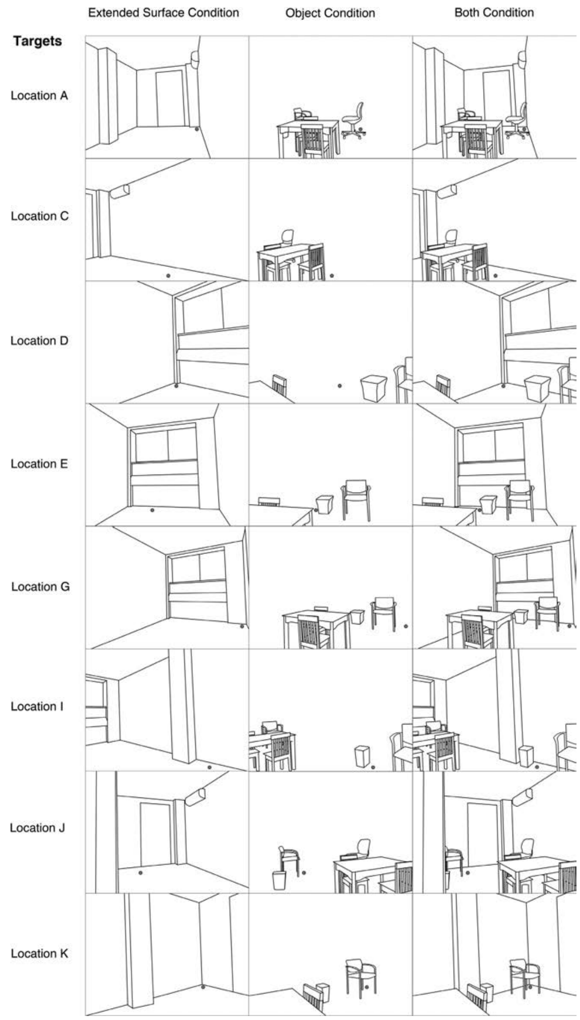

Fig. 3.2. Line drawings depicting each of the eight target locations used in the interpretation and evaluation tasks. The left column presents the extended surface drawings, depicting only the walls, floor, ceiling, outline of the door and window frames, and the air conditioner. The center column presents the object drawings, depicting only the objects in the room. The right column presents the drawings depicting both the extended surfaces and the objects together. One dot (here, in gray) in each picture indicates a target location in the room. Locations A, D, G, and K are all corner targets (in which the targets are directly at the junctions of two extended surfaces), and Locations C, E, I, and J are all targets near objects (in which the targets are right next to objects).

Experiment 1

Overview

In Experiment 1, children completed a line drawing interpretation task, in which they were shown drawings of the room and were asked to place a stuffed animal at locations in the room indicated by the red dot that appeared in each drawing. One group of children saw depictions of the room's extended surfaces, one group of children saw depictions of the room's objects, and one group of children saw depictions of both surfaces and objects together. We examined whether children's performance at different target locations differed for the different types of drawings. We then asked whether the children who were presented with the highly typical drawings of surfaces and objects together performed better than those who were shown the less familiar drawings presenting only the extended surfaces or only the objects. If children use only extended surface information or only object information, albeit in a flexible fashion, then they may not benefit from the simultaneous presence of both surfaces and objects in pictures.

Participants

One-hundred and forty-four 4-year-old children (72 females; mean age = 4;5, range = 4;0–4;11), participated in a line drawing interpretation task. Children were recruited by mail and by posted flyers in a middle-class area in the northeast United States. Most children were Caucasian. Children were randomly assigned to see drawings of extended surfaces only (N = 48), objects only (N = 48), or both types of information together (N = 48). Data were collected from January 2013 through January 2014.

Procedure

After children entered the room, they were acclimated to it by standing in the center and turning around to point to each of the four walls, each of the four corners, and each of the eight objects. Before the test trials, two practice trials were presented, using color rather than geometry to specify a target location: Children were asked to put a small stuffed animal on either a blue or green disk in the center of the room after the experimenter pointed to either a blue or green circle in the center of an otherwise blank laminated sheet of paper. During the test trials, children stood in the center of the room with the experimenter, were shown line drawings of the room belonging to only one set (extended surfaces only, objects only, or both surfaces and objects), and were asked to place a stuffed animal in the room on the locations indicated by the red dots in the drawings. Before the start of the next trial, children picked up the animal and returned to the center of the room. Six of the eight drawings were presented to each child, three drawings depicting different targets located in the corners of the room and three drawings depicting different targets located near objects in the room. Picture presentation order, facing direction (to one of the room's four walls), and the choice of six of the eight drawings were all counterbalanced across children. Each of the eight target locations was assessed 35, 36, or 37 times (depending on the target location) for each drawing type. On every trial, the response location was recorded. Because there were 12 possible response locations, chance was 1/12 (0.08). Three outcome variables were calculated for each child: the total proportion of correct placements (of the six), the proportion of correct placements for the targets in the corners of the room (of the three), and the proportion of correct placements for the targets near objects in the room (of the three).

Results

We first investigated whether the children who navigated a room using pictures that displayed both extended surface and object information together performed better at placing the animal in the indicated locations than children who navigated by pictures displaying only one type of information. Second, we examined whether success differed by target location in the two groups of children who saw only one type of information in pictures: Did children who used pictures with extended surface information perform better at target locations in corners while children who used pictures with object information performed better at target locations near objects? Finally, we revisited children's performance in the condition presenting both types of information to ask whether they interpreted pictures by considering extended surface information and object information together, or instead by switching flexibly between the two types of information, depending on the target location. With these analyses, we begin to evaluate whether familiar pictures of scenes, depicting both extended surfaces and objects, allow young children to relate layout information to landmark objects.

We first performed a two-way analysis of variance (ANOVA) testing whether children's proportion of correct responding was affected by sex and drawing type, which were included as between-participants variables. The analysis revealed no main effect of sex [$F(1, 138) = 0.07$, $P = .794$, $\eta^2_p = .00$ (responses were thus collapsed across sex for all further analyses), but a significant effect of drawing type [$F(2, 138) = 3.91$, $P = .022$, $\eta^2_p = .05$]. Post hoc, one-sided Dunnett's tests evaluated the advantage of having both types of information in drawings versus only one type and determined that children performed better in the both condition [$M = .45$, SD = 0.21] compared to the extended surface [$M = .36$, SD = 0.22], $P = .037$, or object conditions [$M = .34$, SD = 0.19], $P = .009$. Children presented with pictures of extended surfaces and objects together performed better overall than children presented with only one type of information in pictures.

We next tested whether children's proportion of correct responding at corner and object target locations was affected by drawing type using a 2 x 2 mixed-factor ANOVA, with target location (at a corner or at a landmark object) as the within-participants variable and drawing type (surfaces only or objects only) as the between-participants variable. The analysis revealed no main effects but a significant Target Location x Drawing Type interaction [$F(1, 94) = 6.78$, $P = .011$, $\eta^2_p = .07$, Fig. 3.3]. To better understand the nature of this interaction, we determined the simple effects of each variable using orthogonal contrasts. Children who saw drawings depicting only the room's extended surfaces were marginally more successful at finding corner targets than those who saw drawings of just the objects in the room [$t(94) = 1.64$, $P = .105$, Cohen's $d = .34$], and those who saw drawings of objects were significantly more successful at finding targets near objects than those who saw drawings of extended surfaces [$t(94) = -2.05$, $P = .044$, Cohen's $d = .42$].

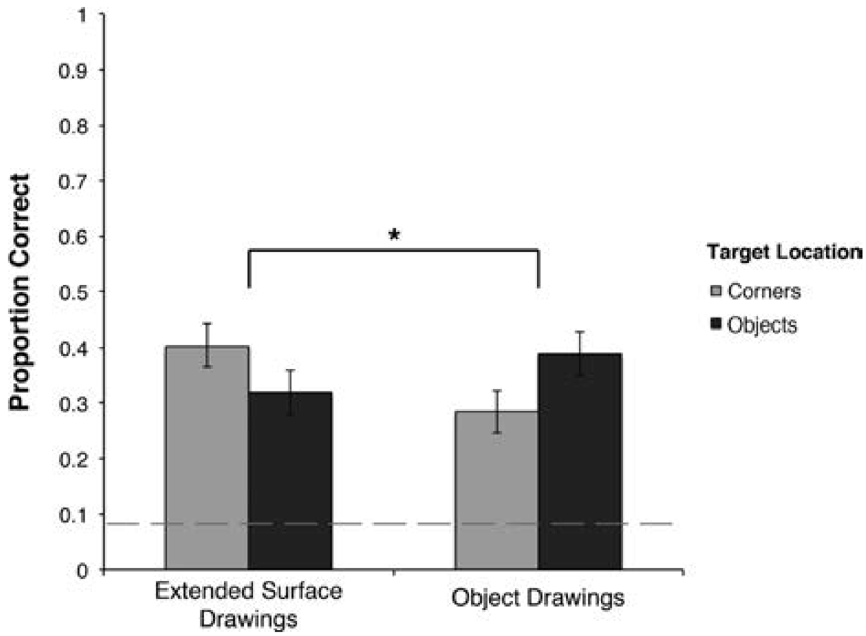

Fig. 3.3. Children's performance on the interpretation task at targets located in the corners of the room or near objects in the room when they were asked to use either extended surface information or object information in drawings. The gray dotted line at 0.08 indicates chance performance. *$P < .05$

Given these moderate differences in children's use of each type of information in drawings depending on the location of the target, we revisited children's performance in the condition presenting both surfaces and objects together to determine whether their greater performance overall could be explained by a flexible use of only one type of information at a time, as has been shown in other studies. Specifically, did children use depictions of extended surfaces and objects together so as to disambiguate between a corner target with a chair on its left versus on its right or between an object target with a corner on its left versus on its right? Or, did children use only one type of information (the extended surfaces or the objects) to find each target location in the room, flexibly selecting the more informative type of information on each trial? To distinguish between these possibilities, we compared the responses of children in the condition with both types of information to the responses of children in the condition presenting the one type of information that yielded higher performance at each target location.

At none of the eight target locations did children perform better in the condition with both types of information than in the better of the two conditions with only one type of information [*P*s > .950, Bonferroni corrected; Fig. 3.4*A*]. Moreover, children's average performance in the condition with both types of information was not superior to their average performance with the drawings presenting the one type of information that was more informative for each target location [*P*s = 1.000; Fig. 3.4*B*]. These findings suggest that children in the condition with both types of information did not combine information about surfaces and objects but rather focused on the more informative type of spatial information for each particular target location.

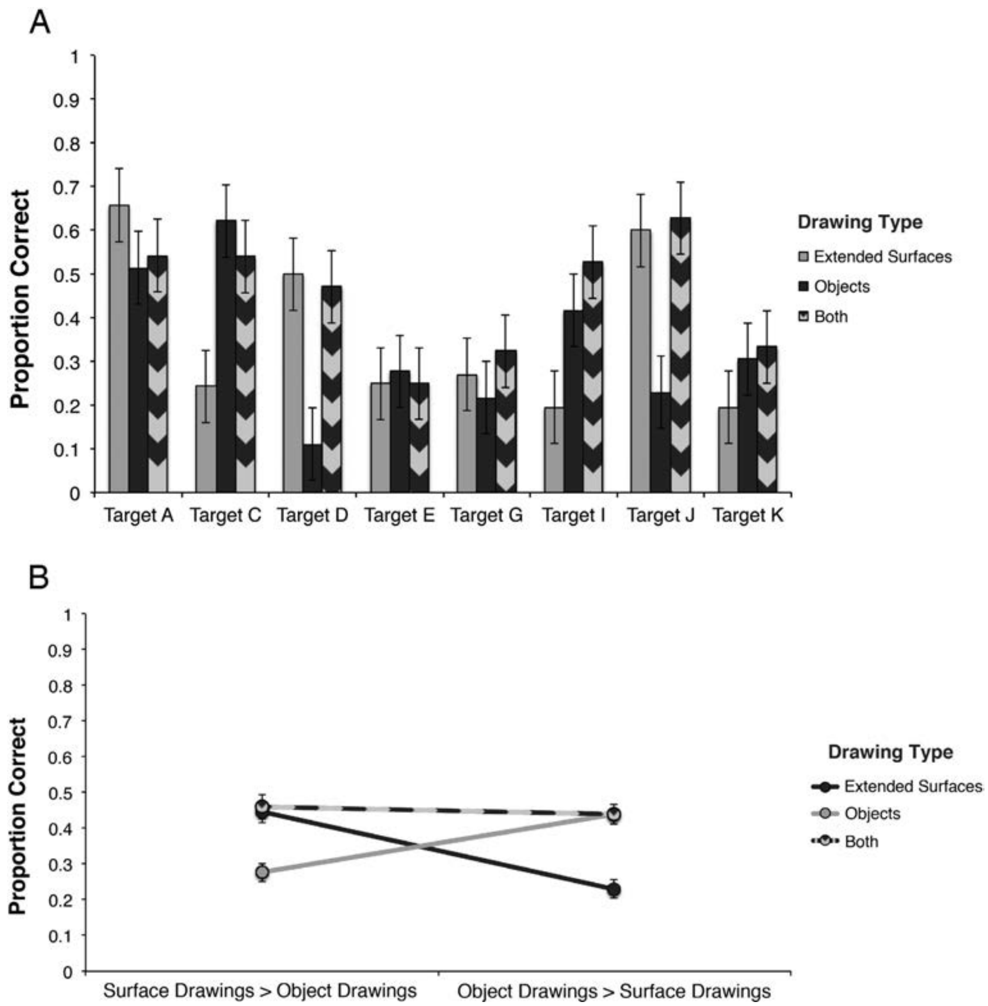

Fig. 3.4. (*A*) Children's performance on the interpretation task at each target location using extended surface drawings, object drawings, and both drawings, the last of which depicted both extended surface and object information together. (*B*) Children's average performance at targets in which performance was better with the surface-only drawings or object-only drawings broken down by the three drawing types.

This failure to find a difference between children's performance in the condition with both types of information and children's performance in the better of the two conditions presenting only one type of information does not allow us, however, to positively conclude a lack of difference. To provide evidence for such a lack of difference, we calculated the average 95% confidence intervals, in standard deviations, above and below which it was unlikely that the addition of the missing information to the two drawing types presenting only one type of information would improve or worsen performance. The addition of the missing information was unlikely to improve performance by more than 0.39 SD, and it was just as likely to worsen performance by the same factor, -0.39 SD. These values contrast with the range of improvement offered by the more relevant, compared to less relevant, information, where the bounds of the 95% confidence interval indicate improvement only, ranging from 0.28 to 1.05 SD. These results more strongly indicate that children's overall success in interpreting drawings that depicted both extended surfaces and objects together likely reflected their ability to flexibly use one type of information or another in the drawings, rather than their ability to combine depicted extended surfaces and objects to form integrated representations of target locations.

Discussion

When presented with both types of information in drawings, children performed better overall than when presented with only one type of information. Moreover, children's success at different target locations was affected by the information in the drawings. Children were moderately more successful with drawings that depicted extended surface information when targets were located at the corners of the room and moderately more successful with object drawings when targets were located next to objects, although the *P*-value for the former contrast fell short of significance. As such, children's greater success in the condition with both types of information could be explained by a focus on only one type of information at a time: When presented with the more informative pictures containing both extended surface and object information together, children showed no additional advantage of combining this information beyond the performance they achieved with extended surface or object information alone at any particular target location.

Could children's failure to benefit from both surfaces and objects together in pictures be explained by information overload? In tasks that require card sorting by one type of information when multiple types are presented, 5-year-old children perform less well compared to older children when presented with too much information (e.g., Shepp, Barrett, & Kolbet, 1987). In these cases, however, the additional information was either orthogonal to the information on which children needed to focus, and was therefore distracting, or was viewed by younger children as integrated with the other information presented, such that selective attention to that particular type of information was not possible. In the present study, however, the additional information in pictures that depicted both surfaces and objects together was informative rather than orthogonal because it further disambiguated the target locations. Moreover, an abundance of research has shown that surfaces and objects are treated as separate spatial features not only by human children (e.g., Lee et al., 2012a) but also by adults and animals (e.g., Doeller et al., 2008). Finally, investigating the effects of language on children's search behavior reveals that when 4-year-old children are given additional relevant linguistic information about landmarks during a navigation task, they incorporate this information into their representation of the layout and search more accurately (Shusterman et al., 2011). Thus, we do not believe that children's failure to show enhanced performance in the condition with both types of information can be explained by there being too much information in the pictures.

Could children's failure to benefit from pictures in the both condition stem from those pictures presenting more occlusion (i.e., where objects stood in front of surfaces)? We believe such occlusion is also unlikely to account for the lack of benefit in children's responses. Even infants perceive extended surfaces and objects as continuing behind occluders (e.g., Kellman & Spelke, 1983; Termine, Hrynick, Kestenbaum, Gleitman, & Spelke, 1987). Moreover, if the natural patterns of occlusion in pictures of furnished rooms cause problems for young children, it is unlikely that these kinds of pictures would be so prevalent in the most popular and valued picture books for young children (see Supporting Information).

We thus conclude that the children in the interpretation task of Experiment 1, who saw pictures with both extended surfaces and objects together, performed no better on each target location compared to children who saw the one, more informative type of information because these children failed to integrate the two types of spatial information. Even when presented with highly realistic and typical spatial symbols, young children show limited ability to combine information about surfaces and objects to enhance their symbol-driven navigation.

Despite this limitation, different groups of children relied on depicted surfaces or objects with similar overall success. The line drawing evaluation task in Experiment 2 (below) begins to investigate whether this flexibility is strategic or automatic by probing whether children recognize, when reading spatial symbols, that depictions of surfaces are more informative in specifying locations at the corners of extended surfaces and that depictions of objects are more informative in specifying locations near objects. This recognition could support children's differential success at corner and object targets. On the other hand, if children do not recognize the relative importance of extended surface or object information in specifying target locations, then their selective attention to depicted surfaces or objects may happen more automatically.

Experiment 2

Overview

In Experiment 2, children completed a line drawing evaluation task, in which they were asked which of two drawings—one depicting just the extended surfaces of the room and one depicting just the objects in the room (Fig. 3.2)—they thought better indicated a target location either at a corner or near an object in the room (Fig. 3.1). The purpose of this task was to examine what information children felt was important in relating a drawing to the environment it represented. If spatial symbols allow children to identify the relevant information for specifying particular target locations, then they should indicate that extended surface drawings are better depictions of targets located at room corners and that object drawings are better depictions of targets located next to objects. In contrast, if children engage extended surface and object information during symbolic spatial tasks more automatically, then they may not be aware of the information in pictures that they use to find different target locations.

Participants

The first 96 children (49 female, mean age = 4;5, range = 4;0–4;11) who participated in the line drawing interpretation task (32 from each of the three drawing-type conditions) also participated in a line drawing evaluation task. Forty-eight of these children completed the interpretation task followed by the evaluation task, and 48 completed these tasks in the opposite order.

Procedure

Before the test trials, two practice trials were presented, using color rather than geometry: Children were shown one blue and one green disk in the center of the room and then were shown two laminated sheets of paper, one depicting blue and green circles and the other depicting purple and pink circles. Children were asked, "Which is a better picture of these two spots in the room; Which picture helps us find these spots better?" Test trials consisted of the two target locations that the child was not tested on in the line drawing interpretation task. Children were shown two drawings of each of these locations, one from the set depicting only the room's extended surfaces and one from the set depicting only the objects in the room (Fig. 3.2). For each child, the extended surface drawing was presented on the left for one trial and on the right for the other trial. The presentation order, facing direction (to one of the room's two walls that allowed the target location to be in full view), and the order of the left/right positions of the drawing types were counterbalanced across children. Using the same language as in the practice trial, every child was asked to evaluate one pair of drawings depicting a location in a corner of the room and one pair of drawings depicting a location near an object in the room.

Results

The first set of analyses investigated whether children's evaluation of pictures mirrored their interpretation of pictures in the task of Experiment 1: Do children think that drawings of extended surfaces are more informative depictions of target locations in the corners of the room and drawings of objects are more informative depictions of target locations near objects in the room (Fig. 3.3)? Because these 96 children completed the tasks in both experiments, the second set of analyses tested for relations between children's interpretation of pictures in Experiment 1 and their evaluation of pictures in Experiment 2. We first test for order effects between the two tasks, and then we analyze the correlations between performance on these tasks across children. Such correlations would suggest that the interpretation and evaluation of the picture geometry are related, even if children's explicit judgments do not reveal that relation.

Preliminary analyses showed no significant differences between male and female children in their evaluation of whether extended surface drawings or object drawings are better depictions of targets in the room [$t(94) = 0.76$, $P = .450$, Cohen's $d = .16$]. Responses were thus collapsed across sex for all further analyses.

We performed a 2 (target location—at a corner or near an object) x 2 (drawing type—surfaces only or objects only) ANOVA on children's evaluations of the drawings. In contrast to the findings for the interpretation task, we found a main effect of drawing type: Children thought that drawings of objects were more informative than drawings of surfaces [$F(1, 95) = 13.13$, $P < .001$, $\eta^2_p = .12$, Fig. 3.5]. We also found no interaction between drawing type and target location [$F(1, 95) = 1.70$, $P = .196$, $\eta^2_p = .02$]: Children thought that object drawings were more informative regardless of whether they depicted target locations in corners or near objects.

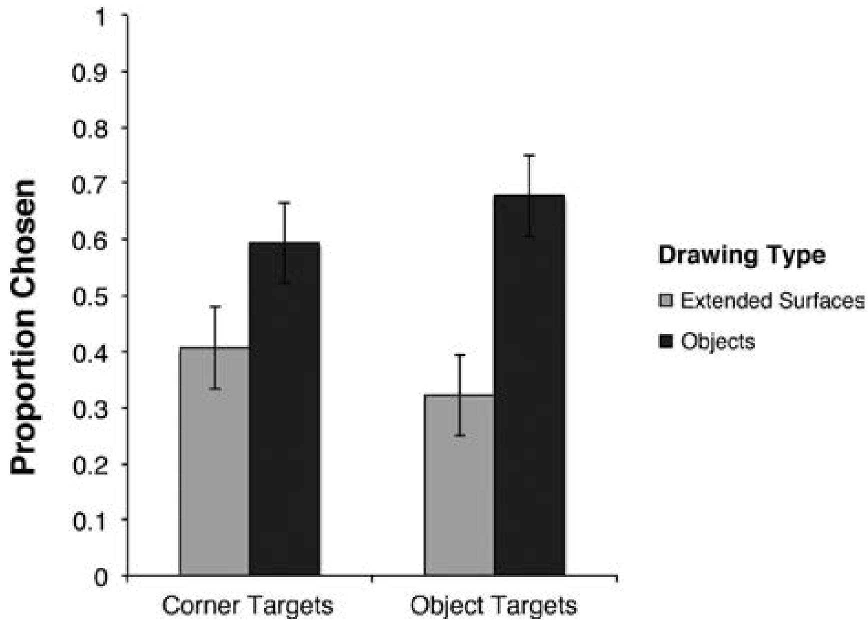

Fig. 3.5. Children's performance on the evaluation task, where they were asked to judge whether extended surface information or object information in drawings better indicated targets located either in the corners of the room or next to objects in the room.

We next tested for implicit relations between children's performance in the interpretation and evaluation tasks by evaluating whether children's performance on the interpretation task of Experiment 1 was affected by whether they completed that task before or after the evaluation task of Experiment 2. A 2 (Task Order) x 3 (Drawing Type) x 2 (Target Location) mixed-factor ANOVA revealed no significant main effect of Task Order [interpretation task first: $M = .37$; evaluation task first: $M = .32$, $F(1, 90) = 0.81$, $P = .372$, $\eta^2_p = .01$], no Task Order x Target Location interaction [$F(1, 90) = 2.65$, $P = .107$, $\eta^2_p = .03$], no Task Order x Drawing Type interaction [$F(2, 90) = 1.85$, $P = .164$, $\eta^2_p = .04$], and no three-way interaction among these factors, $F(2, 90) = 1.24$, $P = .295$, $\eta^2_p = .03$.Thus, children who evaluated the pictures before using them to find target locations in the room performed no better at finding those locations than did other children. Asking children about the pictures did not enhance their strategic use of the information that the pictures presented.

A second ANOVA with the same structure tested whether there was any effect of task order on children's responding at the two types of target locations in the evaluation task of Experiment 2. For this analysis, children's responses on the evaluation task were scored as the proportion of choosing the drawing of extended surfaces for targets near corners and the drawing of objects for targets near objects. This analysis also revealed no significant main effect of Task Order [interpretation task first: $M = .57$; evaluation task first: $M = .51$, $F(1, 90) = 1.00$, $P = .319$, $\eta^2_p = .01$], no Task Order x Target Location interaction [$F(1, 90) = 0.31$, $P = .580$, $\eta^2_p = .00$], no Task Order x Drawing Type interaction [$F(2, 90) = 2.26$, $P = .110$, $\eta^2_p = .05$], and no three-way interaction [$F(2, 90) = 1.99$, $P = .143$, $\eta^2_p = .04$]. Thus, children who first used pictures to find locations in the room were no more likely than other children to judge that the pictures of surfaces were better at specifying corner locations and that the pictures of objects were better at specifying locations near objects. Using the pictures to find targets in the room did not enhance children's awareness of the useful information that the pictures presented.

Finally, a correlational analysis revealed that children who scored better on the interpretation task were not more likely to respond that surface drawings were more informative depictions of corner targets, and object drawings were more informative depictions of targets near objects [$r(94) = .090$, $P = .381$]. There was no correlation between children's judgments that extended surface drawings were better depictions of corner targets and their actual performance at those targets [$r(94) = .032$, $P = .754$] and no correlation between children's judgments that object drawings were better depictions of targets near objects and their actual performance at those targets [$r(94) = .081$, $P = .434$].

Discussion

Children judged that object drawings were more informative of a target's location, regardless of whether the target was located at a corner near at an object. Children's evaluations contrast with their performance in the interpretation task of Experiment 1, which showed an interaction between picture type and target location, with no overall advantage for pictures of objects. In addition, there was no evident relation between children's judgments in the evaluation task of Experiment 2 and their performance in the interpretation task of Experiment 1. Children's higher evaluation of drawings of objects thus appears to operate independently of their actual use of the information in drawings, which varies depending on the locations of the targets that the drawings specify. These findings suggest that children's selective and adaptive use of surface or object information in pictures is not driven by explicit attentional mechanisms in which pictures allow children to identify what information is relevant in specifying certain target locations in the environment.

General Discussion

Children in the present study flexibly extracted different information from pictures depending on the location of the target that they were asked to find. Specifically, they showed a moderate tendency to use depictions of extended surfaces to find targets located in the corners of the room and depictions of objects to find targets located near objects in the room. Moreover, when presented with drawings depicting both surfaces and objects, children failed to integrate the two types of information to distinguish, for example, between a corner with a chair on its left versus on its right. Although previous studies have found that children more easily extract the content of symbols when those symbols represent scenes with highly visual fidelity and in familiar formats (Callaghan, 2000; Ganea et al., 2008; Liben & Yekel, 1996; Simcock & DeLoache, 2006, 2008), children in the present study performed no better with familiar-looking drawings of surfaces and objects together than with less familiar drawings that presented only the room's surfaces or only its objects.

These limitations echo those found in previous studies, which investigated children's ability to relate surface and object information using identical or similar pictures across different environments (Dillon & Spelke, 2015; Dillon et al., 2013). Dillon and Spelke (2015), for example, used similar perspectival pictures to indicate locations in an extended surface layout and on a manipulable object. They found that with the pictures of the layout, children located targets more successfully at corners, but with the pictures of the object, children located targets more successfully near landmarks. The same pattern of success, dependent on target location, was found in the present study, even though the present study varied the information in the pictures while keeping the referent of those pictures identical (Dillon & Spelke, 2015, varied the referent while keeping the pictures nearly constant). Thus, the limitations that children exhibit during early spatial-symbol reading are evident even when children are presented with the sorts of scenes and pictures of the scenes that they often encounter in their daily lives. Moreover, these results indicate that, unlike spatial language (Shusterman et al., 2011), spatial symbols may not encourage 4-year-old children to relate surface and object information during a search task.

The present study also brings to light a striking limitation to children's own knowledge and evaluation of their sensitivity to spatial information: Children chose drawings of objects as more informative about all target locations in the room. Such a failure may reflect a greater attention to objects than to surfaces in drawings or in the environment as much of toddler and preschool-aged children's perceptual development is defined by shifts in their attention from parts of objects to objects' global shapes (Smith, 2009; Smith & Jones, 2011; Yu, Smith, Shen, Pereira, & Smith, 2009). Moreover, most of preschool children's own drawings depict object information only: objects are often centered, floating randomly, or aligned on the page (see Winner, 2006 for a review). Additionally, although pictures with both surfaces and objects were by far the most prevalent among the Caldecott Winners, children may be sensitive to the significant differences in the percentages of object-only versus surface-only pictures in such books (see above and Supporting Information). Finally, it is possible that a simple preference for object drawings guided children's judgments of the usefulness of pictures in Experiment 2. We find this possibility unlikely, however, based on children's performance in the practice trial for that experiment. Children successfully judged that the practice picture with the blue and green dots versus purple and pink dots would "help us find these [blue and green] spots better" (the same language used in the test trials), despite some children having explicitly expressed a preference for the purple and pink dots. Thus, success in these practice questions also indicates that children likely did not interpret the test questions as probing their picture preferences.

Although the present study reveals limits to young children's use of information in pictures, it does not reveal whether older children and adults spontaneously navigate by pictures in a more integrated and explicit fashion, as they do during navigation without spatial symbols (e.g., Hermer & Spelke, 1994; Hermer-Vazquez et al., 2001). Moreover, it does not specify how young children allocate attention to pictures and how this attention might change through development. Using head-mounted cameras or eye-tracking devices, for example, may help to determine where children allocate attention during picture interpretation. Such a measure might also reveal differences between children who do and do not integrate surface and object information (as in, e.g., James, Jones, Smith, & Swain, 2014).

Finally, the present study does not indicate whether the ability to integrate spatial information during picture reading relates to more abstract spatial abilities such as those that support learning of Euclidean geometry. Euclidean geometry focuses on abstract lines and points, and on their relations of distance and angle, which are common to physical surfaces and objects. Although preschool children attend primarily to distance but not angle when they navigate through extended surface layouts (e.g., Lee et al., 2012a), and they attend primarily to relative length and angle but not distance when they recognize forms and objects (e.g., Izard & Spelke, 2009), adults and older children must integrate representations of distance and angle in order to solve even the simplest problems of Euclidean geometry (e.g., "What happens to the third angle of a triangle when the other two angles get bigger?"). Research suggests that such integration is achieved by about 12 years of age (Izard et al., 2011b), but some aspects of Euclidean understanding remain tenuous, even for educated adults (Goldin, Pezzatti, Battro, &

Sigman, 2011). Because the familiar task of recognizing depicted scenes elicits attention both to extended surfaces and to objects, interventions that increase children's awareness of their attention to different geometric information in spatial symbols might inform a pedagogy aimed at revealing the fundamental entities and relations of abstract geometry.

In addition to these applications, the present findings suggest that pictures of all kinds serve as media in which children deploy different symbolic spatial skills flexibly and automatically, without the need for explicit strategies modulating attention to certain spatial features over others. Such symbols represent both 3D scenes and objects, joining the spatial information guiding navigation with the spatial information used to recognize objects by their shapes. Although this information is not integrated in children's use of spatial symbols, cognitive scientists may elucidate the processes by which geometric abstractions, rooted in more complex geometric symbols like those underlying Euclidean constructions, arise by charting the development of children's engagement with the spatial relations presented in more common and easily understandable spatial symbols, including maps, perspectival art, and especially the ordinary drawings that are ubiquitous in children's lives.

Supplemental Information

To determine the familiarity of pictures depicting only extended surfaces, only objects, or both types of information to the children in the present study, we attempted to analyze the pictures in all of the children's books that have won the Caldecott Medal over the last 20 years. The Caldecott Medal is given to the artist of the year's most distinguished picture book for children. Two hypothesis-blind research assistants coded the pictures in these books as depicting exclusively extended surfaces, exclusively objects, or both types of information. One research assistant coded all of the books that were available in the local library (15 out of the past 20 winners). A second research assistant recoded 7 of those 15 books, and the reliability of the two coders was high, $r = .98$. The primary coder determined that 90.3% of 474 pictures in these 15 books included both surface and object information together, while only 2.5% of pictures included just surface information, and 7.2% of pictures included just object information. Chi-square tests revealed a significant effect of drawing type [$X^2(2, N = 474) = 693.62$, $P < .001$] and significant differences between all pair-wise comparisons across the drawing types (Bonferroni corrected; Both versus Surfaces only [$P < .001$], Both versus Objects only [$P < .001$], and Surfaces only versus Objects only [$P = .004$]. Thus, the most successful picture books for children overwhelmingly present drawings that depict both surfaces and objects together. Moreover, drawings that present objects without surfaces are more common than those that present surfaces without objects.

Conclusion

The three papers in this dissertation provide evidence that the geometric content of our evolutionarily ancient systems for navigation and form analysis also supports young children's uniquely human use of spatial symbols. Moreover, these papers show that despite their evolutionarily extraordinary ability to read maps and pictures, young children nevertheless do not integrate the different geometries of the two ancient systems. As a result, their symbolic geometry remains too impoverished to support reasoning about the more complex spatial relations of formal geometry that relate distance and angle. While this work has shown how we as humans go from the physical scenes and objects in the world to the scenes and objects in symbolic maps and pictures, it has also raised a new question: How do we go from spatial symbols to that quintessence of human thought, abstract geometry?

From spatial symbols to abstract geometry

My work with older children (Dillon & Spelke, in revision) reveals that by 10-12 years, not only does spatial symbol reading become much richer in its use of geometry, but also, success in spatial symbol reading predicts success in answering questions about the properties of planar figures (e.g., "What happens to the third corner of a triangle when the other two corners are moved farther apart?") across children. Prior to this work, no evidence had linked the symbolic geometry children access early in development during map reading to the more abstract geometric intuitions children recruit later when making judgments about points, lines, and figures on the Euclidean plane.

In particular, the follow-up work I describe below addresses whether developmental changes in the use of simple geometric maps are associated with the development of more abstract and explicit reasoning in the geometric domain. Because such map reading emerges spontaneously, long before an abstract understanding of geometry, and because it initially relies on isolated distance or angle information in young children, the hypothesis that drives this work is that children come to use distance and angle relations in a more integrated fashion over development during navigation by geometric maps. Such integrated use of distance and angle information during map reading, moreover, would also predict children's more abstract use of distance and angle relations in an explicit geometric reasoning task probing an understanding of the properties of planar triangles. Abilities to navigate by geometric maps and to reason about abstract, unseen parts of triangles may both depend on an emerging, underlying capacity to relate distance (a key property of the perceived navigable environment) to angle (a key property of perceived object shape).

The participants in this study (Dillon & Spelke, in revision) were 6- (N = 32,12 females; mean age 6;7, range 6;0-6;11), 10- (N = 32; 12 females; mean age 10;5, range 10;0-10;11), and 12-year-old children (N = 32; 17 females; mean age 12;6, range 12;1-12;11). They were presented with a map task adapted from the map task of *Paper 1*. In this version of the map task, both the environments and the maps presented fragmented triangles either with sides but no corners or with corners but no sides. On half of the trials (Congruent Condition), the map and environment presented the same geometric features (either sides or corners); on the other half of the trials (Incongruent Condition), they presented complementary features (e.g., a map presenting just the sides of the triangle designated a location in an environment consisting of only the triangle's corners). The extent to which children could relate sides and corners of a triangle across maps and environments during map reading was quantified by comparing their performance when maps and environments presented congruent versus incongruent information.

The same children were also assessed on their geometric intuitions, using an adapted version of Izard et al.'s (2011b) triangle completion task. Children were presented with the bottom two corners of an implied triangle, described as an imaginary navigable layout. For different trials, the corners were altered in their position and angle size by the experimenter, and children were asked, in separate blocks of trials, whether the implied third corner moved up, moved down, or stayed in the same place, and whether its angle size got bigger, got smaller, or stayed the same size. We examined how each kind of transformation affected children's judgments to assess how they related side distances to corner angles when making judgments about planar triangles. We then looked for relations between the map task and the geometric intuitions task across children, controlling for verbal intelligence scores, to investigate whether children's map reading through development predicted their explicit judgments about planar triangles.

In the map task, while 6-year-old children performed better with congruent versus incongruent information across maps and environments [$P = .010$], 10- and 12-year-old children suffered no significant cost associated with incongruent information. Moreover, while 6-year-old children, like 4-year-old children in *Paper 1*, showed no correlation between their performance in the two environments [$r(30) = .24$, $P = .192$], 10- and 12-year-old children showed signification correlations [$r(30) = .45$, $P = .010$; $r(30) = .72$, $P < .001$]. The strength of this correlation was moderated by age across the full sample of children [$\beta = .89$; $P = .010$], with no large differences in the reliability of map performance across age. Thus from 6 to 12 years, the shape representations that children use to read maps in triangular enclosures of sides progressively become more strongly related to those that they use to read maps in triangular enclosures of corners.

In the geometric intuitions task, all three age groups performed above chance on questions probing the location of the third corner of the triangle after changes to the bottom two corners. However, only 12-year-old children performed above chance on the questions probing the angle size of the third corner, while 6-year-old children performed significantly below chance on these questions. Further analyses of children's error patterns suggested that the 6-year-old children responded to both question types using a non-Euclidean strategy based only on size, in which any transformation that made the triangle bigger, for example, made both its distance and angle properties bigger. Moreover, only in the 12-year-old children was success in the location questions correlated with success in the angle questions across children [$r(30) = .36$, $P = .045$], suggesting a consistent Euclidean-based strategy. Finally, age modulated the strength of the relation between children's judgments about the location and the angle size of a triangle's third corner [$\beta = .72$; $P = .044$]. Thus from 6 to 12 years, children become increasingly able to intuit how the distance and angle properties of planar shapes interact with one another, in accord with basic principles of Euclidean geometry.

To determine whether individual children's map performance predicted their performance on the geometric intuitions task, we conducted regression analyses. After accounting for effects of age and verbal intelligence, age-specific regression analyses showed no relation between children's map reading and their geometric intuitions at 6 years [$\beta = .06$; $P = .708$] and only a non-significant relation between performance on these tasks at 10 years [$\beta = .30$; $P = .102$]. In contrast, the two tasks were significantly correlated across children at 12 years [$\beta = .53$; $P = .010$]. By age 12, children's performance on the map task converged reliably with their judgments on the geometric intuitions task.

A final regression analysis examined how developmental changes might affect the relation between map reading and geometric judgments by collapsing across groups and testing for the moderating effect of age on this relation. Across the full sample of children, age significantly affected the strength of the relation between map reading and geometric intuitions [$\beta = .20$; $P = .039$]. Thus, the predictive power of map reading on geometric intuitions tends to grow as children get older.

This study reveals a relation between children's map reading and their reasoning about planar triangles. Moreover, analyses of children's patterns of performance in the map and reasoning tasks suggest that this relation may depend on an emerging ability to relate distances and angles within the same planar figure. Young children's map reading relies in part on geometric representations that humans share with other animals, which allow us to navigate the environment and to recognize the objects in it. These representations, however, have limits that can still be seen in young children's map reading and possibly also in their explicit geometric reasoning. When reading maps, young children rely exclusively on side distance information in an enclosure that presents side walls but not corners, and they rely exclusively on corner angle information in an enclosure of the same overall shape that presents corner angles but not side walls (*Paper 1*). When making judgments about the properties of shapes, moreover, children fail to judge that angle size is conserved over changes in a triangle's absolute scale (Gibson et al., 2014; Izard et al., 2011b).

Nevertheless, those limits are overcome, and our uniquely human success in geometry has a developmental story this study begins to elucidate. By age 10, children's map reading in fragmented environments appears to rely on the same overall shape representation implied by the different fragments, whether only sides or only corners are presented. This finding suggests that children infer missing sides from an enclosure presenting only corners, and vice versa. Developmental changes in map reading, as measured by this study, thus suggest a more integrated representation of the spatial layout and its distances and angles. By age 12, children's judgments about the side and corner properties of planar shapes capture principles of Euclidean geometry. Children's use of more integrated shape representations during map reading may foreshadow this achievement. Our strongest evidence for a link between performance on these two tasks is that as children get older, these tasks become ever more correlated with one another. The strategies that older children use when reading simple geometric maps depicting fragmented figures predicts their responses on an explicit test of Euclidean judgments about abstract triangles.

This finding leaves a further puzzle: Human abilities to navigate by purely geometric maps emerge very early in human development, and yet intuitions about Euclidean figures emerge quite late. Why might these two abilities show convergence through development? This study cannot answer this question. Nevertheless, map reading and geometric reasoning might improve because children develop more abstract and integrated representations of two fundamental geometric capacities, captured by different, early developing geometric representations: the representations of distance and direction that guide navigation and the representations of angle and relative length that guide visual form analysis.

Might maps promote the integration of these representations? Symbols in general allow humans to represent diverse types of information efficiently and may therefore provide a medium in which different information can be held in memory, manipulated, or combined. For example, Arabic symbols allow for the manipulation of exact large magnitudes, and tree diagrams allow for the efficient representation of biological taxonomies. Maps may likewise allow for the efficient representation of diverse features of the environments that they represent. In particular, maps represent both 3D scenes and objects, joining the distance and directional information used to navigate with the relative length and angle information used to recognize objects by their shapes. Like other spatial symbols, maps are culturally widespread (Deloache, 2004), and they are similar to the pictures that children encounter and interpret from an early age (Bloom & Markson, 1998). When a map depicts only the sides of a triangular enclosure that is composed only of corners, and the map is presented by an apparently helpful adult as a useful source of information about that enclosure (perhaps through specific kinds of linguistic cues, e.g., Winkler-Rhoades, 2011), children may reanalyze the sides on the map to recover information about the corners in the environment (see Callahan & Corbit, 2015, for a discussion on intentionality in children's use of spatial symbols). Children's use of maps may thus encourage their integration of different geometric elements of the environment.

Although the findings in this study raise such a possibility, they cannot confirm it. The observed correlations between children's map reading and their explicit geometric intuitions remain after controlling for verbal intelligence scores, suggesting that these changes are not wholly explained by differences in language experience or vocabulary size. Nevertheless, these correlations could rely in part on other developments, including age-related changes in sensitivity: to objects' visual properties (Kaldy & Blaser, 2009); to the robustness of shape perception, attention, and working memory (e.g., Gibson, 1969; Giofrè, Mammarella & Cornoldi, 2014); to aspects of executive function that allow older children to shift more effectively from one source of information to another (Bull & Scerif, 2001); or to capacities for analogical reasoning that allow children to apply geometric relations to different types and properties of objects (Loewenstein & Gentner, 2005). Further experiments could test these possibilities by probing correlations between developmental changes in the present tasks and changes in these other capacities.

Even if the correlation between performance on the map task and intuition task does depend on the combination of distinct geometric representations of distance and angle, the present findings would not reveal whether the experience of reading maps causes advances in children's geometric reasoning. Training experiments are needed to explore whether tasks that exercise map reading play any causal role in the development of geometric intuitions about planar figures and, if so, what cognitive changes underlie such effects (see Uttal, Meadow, Tipton, Hand, Alden, & Newcombe, 2013 for a comprehensive review of spatial training studies). Through a collaboration with my advisor Elizabeth Spelke and the MIT economist, Esther Duflo, I have found that training preschool children's spatial skills can lead to gains both in core geometric abilities as well as school learning in geometry (Dillon, Kannan, Dean, Spelke, & Duflo, in revision). We showed this in a large randomized controlled trial in poor areas of Delhi, India, which tested a mathematics curriculum that included both form-analysis and map-reading games closely resembling the tasks outlined in this dissertation (*Papers 1 & 2*). Such a training study indicates that core geometry can improve with practice and that this improvement leads to gains in the understanding of geometry used in formal schooling. In the context of the present dissertation, it might be particularly informative to test whether training with fragmented maps and environments paired incongruently improves 10-year-old children's ability to engage in geometric reasoning about planar figures more than training with the same maps and environments paired congruently.

The present findings also raise questions concerning the processes by which older children and adults reason about abstract geometric figures. Do older children use mental simulations to complete missing parts of figures when answering questions about them? Or do they instead apply some sort of propositional knowledge, for example, that the three internal angles of a triangle must sum to a constant? If success on an explicit geometric reasoning task, such as a triangle completion task, depends in part on mental simulation processes, then how do older children and adults go beyond these simulations to identify the specific aspects of shapes that enter into geometric theorems? If success depends in part on propositional knowledge, then how do children select which propositions are applied to particular spatial arrays?

Further research, applying chronometric, eye-tracking, or computational modeling approaches, could address these questions. In particular, our own recent findings using computation methods with data from adults are beginning to suggest that adults' explicit judgments about shapes are nevertheless strongly tied to processes of mental imagery, not to linguistic or algebraic rules like those that govern other kinds of uniquely human abstract thought (Hart, Dillon, Marantan, Cardenas, Spelke, & Mahadevan, in review). To arrive at this suggestion, we modeled adults' mechanisms of imagery as they visually completed fragmented triangles. As the size of a triangle's base increased, the errors that the adults made increased exponentially. Moreover, adults imagined lines that underestimated the location of a triangle's third corner, making the sum of the triangle's internal angles not constant. Our evaluation of this imaging process has allowed us to explain these curious but characteristic errors that remain present in the explicit geometric reasoning of adults (Dillon & Spelke, in revision; Izard et al., 2011b). This project makes the developmental and evolutionary story of geometry ever more important as we realize that, while we may come to understand how distances and angles relate to one another in planar figures, this understanding may not be so abstract or Euclidean after all.

Finally, given that young children's map reading is related to geometric abilities from our evolutionary past, the question remains as to whether there is any detectable relation of non-symbolic navigation and object recognition in older children's explicit judgments about planar shapes. It is possible that developmental changes in children's map reading and geometric intuitions build on the more limited geometric representations guiding navigation and form analysis. Alternatively, older children might not engage these cognitive systems when relating distances and angles in symbolic or explicit contexts. By testing for effects of training experiments aimed at enhancing older children's navigation or form analysis on children's explicit judgments about the properties of triangles, we may determine whether early developing and evolutionarily ancient systems of representation serve as guides to the judgments that support formal geometry. If our geometric abstractions build on symbolic and non-symbolic geometric skills that arise early in development and are used throughout our lives, then efforts to enhance those capacities through education may benefit from a pedagogy linking the formal systems children must master to the everyday acts of navigation, object recognition, and map reading in which they readily take part.

Why Paleolithic artists didn't draw landscapes

The findings presented in this dissertation raise one further intriguing question that I will address in this final section: Might our core systems of geometry have even shaped our cultural development through historical time? Below I begin to address this question with a case study investigating the development of landscape portraiture. The first extant landscape depicting extended natural scenery was created only 3,500 years ago, tens of thousands of years after Paleolithic depictions of objects and other visual forms. What explains this delay? I offer an explanation by appealing to the present research linking our core cognitive systems of geometry — one for navigation and one for form analysis — to our use of spatial symbols, like maps and drawings. While our system for form analysis, which represents the geometry of objects and visual forms, preserves information necessary to produce a 2D picture, our system for navigation, which represents the geometry of scenes, does not. Our resulting difficulty translating scene-relevant geometry to a 2D drawing may explain the protracted emergence of landscapes in the history of art.

A survey of 3,981 figures across 154 sites in Spain and France revealed that drawings created by our Paleolithic ancestors were limited to: animals, most commonly horses and bison; human figures, rarely depicted and often stylized; tools or weapons; and abstract symbols, composed of simple spots, short lines, or more complex curvilinear and geometric shapes (Wlodarczyk & Sauvet 2000). Jean Clottes (2008), archeologist and surveyor of the Chauvet Cave, describes Paleolithic cave art as characterized by the "abundance of animals and signs, the relative rarity of humans (more numerous in object art), the total absence, at least in a form recognizable by us, of environmental elements (the sun and the stars, trees and plants, rivers and water, mountains and valleys, tents and camp sites)" (p. 20). Why are there no landscapes?

Paleolithic artists do seem to have attempted to draw scene representations, and although these do not cohere as landscapes, they may offer the best evidence that their artists were inclined to depict layout information. For example, at Chauvet, paintings of lions hunting a bison or rhinoceroses facing each other achieve a scene-like result through the juxtaposition of forms (J. Clottes, personal communication, 22 March 2013). Even more remarkable is a diptych at Lascaux that uses the intersection of the cave walls to show two aurochs, one on each wall, seemingly running from a shared starting point towards either side of the viewer (Fig. 4.1).

Taking advantage of such a physical perturbation on the drawing surface may have been a technique used to represent scene information in lieu of drawing its extended-surface geometry. These object-focused scene representations, as such, remain categorically different from the landscape portraits made today (Stilgoe, 2015). Nevertheless, in their very attempt to organize objects and figures into scenes, our Paleolithic ancestors showed their desire to depict layout information. Indeed, landscape depictions that include scene geometry are a universally preferred artistic genre across diverse cultures today (Dutton, 2009). Moreover, Paleolithic humans share with modern humans other aspects of shape depiction. For example, Biederman and Kim (2008) evaluated 215 figures from European cave art to see if they included a linear form that demarcates the junction between two curved surfaces (e.g., where a horse's leg joins with its body). They found that nearly identical proportions of Paleolithic art and art generated by modern lay people depicted this junction. Only a group of trained artists produced the smooth contour junction at a significantly higher proportion. It is thus unlikely that the late emergence of landscapes in the history of art is because early humans did not want to depict them. Rather, I argue that this delay was caused by a deep cognitive hurdle and that our ability to draw landscapes effectively was ultimately due to an accumulation of cultural knowledge sparked by one or more technological innovations that helped us overcome the limitations of our core geometric sensitivities.

Fig. 4.1. A diptych of aurochs at Lascaux Cave, ca. 17000 BCE. This drawing depicts two aurochs running from a shared starting point towards either side of the viewer. In lieu of drawing landscape geometry, the artist created a sense of the scene both by showing part of one auroch occluding part of the other and by taking full advantage of an indented section of the cave wall. Photo: Don Hitchcock (retrieved from: donsmaps.com).

The earliest known landscape dates to 1550 BCE, and it is credited to the Minoans of Ancient Crete (Fig. 4.2). This botanical scene with a few fluttering birds is striking in both its novelty and its limitations. It is novel because somehow its artist was the first known who dared to represent extended surfaces. Nevertheless, it remains as limited as our Paleolithic art, for it lacks a depiction of the layout's geometry (i.e., its extended-surface depth). Like the Lascaux diptych, it exploits the geometry of its locale: The viewer enters the landscape by entering a room. In many ways it thus depicts a scene by using a scene.

Fig. 4.2. The earliest known landscape, credited to the Minoans of Ancient Crete, ca. 1550 BCE, depicts a brightly colored rocky terrain with blossoming lilies and flying swallows, but it provides no depiction of the layout's geometry. Like the Lascaux diptych (Fig. 4.1), it uses the 3D geometry of its locale to create a sense of the layout's space. © Jebulon (retrieved from: Wikimedia Commons)

The protracted development of linear perspective in the history of art may likewise suggest that depicting the geometry of the extended-surface layout is far from intuitive. Although the archeological record is scattered, incomplete, and often indirect, we observe some developments towards linear perspective in the ancient period. Some of the best early attempts at capturing perspective occurred in Roman art, preserved, for example, in the frescos at Pompeii (first century CE, Sinisgalli, 2012). Nevertheless, the knowledge and practice of perspectival drawing in the West were lost with the fall of Rome and only reemerged a millennium later at the end of the Middle Ages. In the early fourteenth century, the Florentine artist Giotto reintroduced the use of perspective, where segments of his paintings would consistently recede according to their position on a local axis (Howard, 2012). Not until the early fifteenth century, however, did artists realize that, from a given view, everything converges to a single point, a realization credited to the Florentine architect, Brunelleschi. Martin Kemp (1990) believes that Brunelleschi applied his knowledge as an architect to measure a scene and then drew it from calculations on his scaled measurements. The artist David Hockney suggests the use of a lens, probably in the form of a mirror, allowing Brunelleschi to trace the 2D reflection from the projected 3D image (Wright, 2003). Historians can debate what allowed perspectival landscapes to emerge, but we are left to wonder about the barriers to our intuitions that hindered their emergence throughout history. Here, recent results from cognitive science and psychology outlined in this dissertation and in other bodies of work can shed light on this puzzle.

Curiously, while our depiction of landscapes required an advance in cultural evolution, biological evolution has always allowed us to navigate landscapes with ease, as I describe in the Introduction to this dissertation. The two core systems of geometry, in particular, allow us to move through the object-filled scenes of our world. While the *navigation* system represents the layout of the environment by absolute distances and directions fixed by the large, extended surfaces in the environment (Ekstrom et al., 2003; Lee et al., 2012; O'Keefe, 1976; O'Keefe & Burgess, 1996; Ono et al., 1991), the *form analysis* system, represents the shapes of small-scale objects and visual forms by the relative lengths and angles of their parts or edges (Biederman & Cooper, 1991; Dehaene, et al., 2006; Gregory, Landau & McCloskey, 2011; Kayaert et al., 2003; Kourtzi & Kanwisher, 2001; Schwartz & Day, 1979; Smith, 2009). Moreover, as this dissertation shows, there are relations between our phylogenetically ancient core cognitive systems of geometry and our uniquely human use of spatial symbols. When young children use an overhead map to find a location in an environment composed of large, extended surfaces, they rely on their core system of navigation. In contrast, when they use the same overhead map to find a location in an environment composed of isolated objects of different shapes, they rely on their core system of form analysis (*Paper 1*). This pattern of results is found not only for children's interpretation of overhead maps in novel environments, but also for their interpretation of perspectival drawings and photographs that refer to typical indoor scenes and familiar childhood objects (*Papers 2 & 3*). These studies thus reveal an ease in young children's interpretation of spatial symbols that is related to an ease in their navigation and form analysis.

Nevertheless, young children's interpretation of spatial symbols is not as easy as it seems. Although their interpretation of spatial symbols relies on the two core systems of geometry, it is also limited by them: In no studies in this dissertation were young children able to use spatial symbols to reinterpret extended surfaces as a collection of lengths and angles (i.e., object geometry), nor were they able to reinterpret objects as relations of distances and directions (i.e., scene geometry). Studies on map reading with older children show that these limitations are overcome by age 10 years in the *interpretation* of spatial symbols (as described above).

Nevertheless, these limitations may not be overcome even through adulthood in the *production* of symbols. Why?

Effective line drawings engage a pre-existing visual pathway by representing the same edge contours that our visual system would pick up anyway from their referents (Sayim & Cavanagh, 2011; see also Kandel, 2012; Tian, Yamins, & Grill-Spector, 2016). As such, depictions both of layout geometry and object geometry enter the visual system on an equal playing field, and the context in which a symbol is presented determines to what core system its content is sent for interpretation (*Papers 1-3*). Line drawing production, however, is not as bipartisan — to accommodate their 2D medium, line drawings have to be produced as visual forms. And in fact, until the first landscape, everything depicted as a visual form in an artistic representation *had already been cognitively represented* as a visual form by the core systems of geometry. The core system of form analysis, that is, already represents objects by preserving the very lengths and angles that must then be drawn on the page.

It is true, however, that when an object rotates in 3D depth, information about its shape is more or less robustly preserved by our core system of form analysis. An object's non-accidental properties (NAPs), such as whether an edge is straight or curved, or whether it forms a junction, are best preserved, as these properties change little when an object is rotated in depth. Metric properties (MPs) on the other hand, such as the degree to which an edge is curved, its length and angle relations, or the aspect ratio of an object's parts, are represented less robustly, as these properties change more when an object is rotated in depth.

Differences in the preservation of object shape information are universal across human cultures. Modern adults, whether from an industrialized society or from a remote tribal society with little exposure to regular artifacts, are similarly sensitive to NAPs and MPs. Biederman et al. (2009) tested NAP and MP sensitivity in undergraduates from the University of Southern California and adults from the Himba tribe, an indigenous people in northern Namibia, using a match-to-sample task. Overall performance was essentially equivalent between the two groups, and there was also an equivalent advantage for recognizing NAPs over MPs.

This lack of robustness to MPs presents a challenge to an artist who is trying to capture object geometry in the third dimension. Through development, representations of object geometry become more salient and rotationally invariant (Landau et al., 2006; Slater et al., 1991; Smith, 2009). And this development is mirrored by changes in children's drawings: Around age 9-10 years, children cease to draw a tabletop as a rectangle (its actual shape) and begin to depict it as a parallelogram or trapezoid (closer to how it would look from one viewpoint in space; Freeman, 1980; Willats, 1995). Indeed, children at this age also begin to incorporate objects' relative sizes and vertical positions on the page as further depth cues (Cox, 2005). Paleolithic artists thus likely represented basic shape properties like NAPs, lengths, and angles just as modern humans do today.

The core system of navigation, however, does not represent landscapes by its relative lengths and angles. Rather, it represents a landscape as a collection of absolute surface distances and directions. As such, two translations are required to draw a landscape: the first a translation of geometries, in which navigationally relevant distances and directions are translated into forms with lengths and angles; the second a translation of spatial entities, in which large-scale surfaces are translated into small-scale visual forms. These translations required for depicting landscapes may have been a cognitive hurdle too high throughout the history of art, even if their ready learnability today makes landscape drawing seem less daunting of a task (Gombrich, 2000).

Artistic training offers techniques that allow us to sidestep our otherwise limited geometric capacities: turning a picture upside down; superimposing gridlines; shifting attention between global and local spatial features; attempting to avoid/overcome an automatic analysis of layouts and objects by attending to negative space; etc. (Chamberlain & Wagemans, 2015). Kozbet & Seeley (2007), moreover, suggest that artistic representation is deliberate and systematic and that an artist's specialized declarative knowledge and trained motor actions shift their attention to enhance the encoding of 3D spatial features.

Contemporary cognitive science and psychology may also inform our understanding of how one can learn to draw landscape elements. Although our core system of navigation relies essentially on the distance and directional information describing the extended surface layout, scene-selective regions with different geometric sensitivities and functions have been identified in the human cortex, and their characteristics provide nuance to our understanding of the core navigation system (Epstein, 2008). For example, one scene-selective region, the parahippocampal place area (PPA; Epstein & Kanwisher, 1998), underlies scene recognition and categorization (Walther, Caddigan, Fei-Fei & Beck, 2009), and it appears insensitive to changes in a scene's distance and directional information (Dilks, et al., 2011; Persichetti & Dilks, 2016). Such insensitivity presents a puzzle: How can a scene-selective region not represent the information relevant to navigating a scene? Recent work has revealed that the PPA prioritizes a scene's contour junctions, capturing a non-accidental shape property that is typically associated with object recognition and form analysis (Choo & Walther, 2016; Walther & Shen, 2014). Moreover, the PPA has also recently been shown to detect changes in the "shape" of a scene, specifically changes in the relative lengths and angles of its extended surfaces (Dillon, et al., in revision). Such findings indicate that across the scene-processing network, the junctions, lengths, and angles that are used to create 2D perspectival drawings of scene geometry do get represented. Nevertheless, the representation of this geometric information is localized in a brain region dedicated to scene recognition and categorization, not to scene navigation. As such, if it is possible to engage an artist in a process of scene categorization when they are drawing scenes, then it may allow them to more easily access the lengths and angles of scene contours that are needed for drawing a landscape.

The historical record suggests that humans may have drawn overhead maps of their local environment in a time prior to that of the first landscape (e.g., the Neolithic map at Çatalhöyük, which has been dated to ~6600 BCE; Schmitt, Danišík, Aydar, Şen, Ulusoy, & Lovera, 2014). Nevertheless, such maps do not constitute landscapes: They *represent* distance and directional information about the layout but do not *reproduce* it. A map is thus not a depiction of the environment, as is a landscape, but rather a map is a "carefully controlled symbolic abstraction" of it (Downs, 1985, p. 325). In addition, overhead maps like the one at Çatalhöyük appear to rely on the juxtaposition of object-like representations. Thus, as we may see in overhead maps, and as we do see in several of the Paleolithic examples above, a clever artist — whether ancient, child, or amateur — can obviate the challenge of translating landscape geometry in their effort to portray a scene by relying on the lesser challenge of depicting objects, exploiting techniques of juxtaposition, superimposition, or relative size.

Here too, the history of art may recapitulate some aspects of human development. By age three to four, children begin to represent object shape information (Drake & Winner, 2012), and objects predominate drawing content for a long time afterwards (Machón, 2013; Villarroel & Ortega, 2016). Although much work has investigated the development of children's drawings, little of that work weighs in empirically on the present theory I suggest. This rich body of past research evaluates children's drawings for emotional or spiritual content (e.g., Coles), or its capturing of spatial elements reflective of general developmental stages (e.g., Gardner or Machón). Other work (e.g., Hagen, 1985) has explored the specific geometric elements that children and lay adults capture in their drawings, suggesting that properties of our visual system affect our translation of that information on the 2D page. Nevertheless, these analyses do not address my suggestion that different spatial entities, like scenes and objects, may not be equally available for representation given that their recognition and use are both neurally and cognitively dissociated. Still, some parallels between development and the history of art remain overly literal in their suggestion that development fully recapitulates the history of art, with abstract expressionism standing as the pinnacle of both (e.g., Gablik, 1976). My invocation of the development of children's engagement with pictorial symbols relies on recent research, illustrates our cognitive limitations in comprehending and producing pictorial art, and calls for future research exploring pictorial production along specific lines. I suggest that a systematic examination to determine what information children spontaneously draw when attempting to depict a scene, as well as why they depict that information, may further inform our understanding of landscape portraiture over historical time.

Any relation between cognitive abilities shared across species and those abilities unique to humans is bound to be complex. In this last section of the dissertation, I have called attention to a paradox arising from one such relation — our cognitive ease in navigating landscapes, which we share with other animals, and the relatively late development of landscape portraiture, unique to humans. I suggest that our evolutionary inheritance helps to explain our cultural achievement. Both our ability to depict landscapes and our historical delay in doing so may be explained by the contrasting geometric sensitivities of two core cognitive systems that we inherited through evolution and that are evident throughout human development. The constraints of these phylogenetically ancient geometric sensitivities demonstrate the importance of human psychology to this cultural puzzle, for it is ultimately the limitations and flexibilities of the human mind that shape the history of our unique but hard won ability to represent the world in which we live.

Final Remarks

This dissertation presented three papers investigating whether and in what way the non-symbolic, core geometric representations guiding navigation and form analysis in humans and in other animals may come to support uniquely human symbolic and abstract geometric thought. It has done so by providing the results of my investigations into children's capacity for relating the geometric information presented in simple maps and pictures to the scenes and objects that these symbols represent. *Paper 1* found that young children's use of core geometric information to navigate scenes and analyze visual forms correlated with their ability to use geometric information presented in simple overhead maps of fragmented triangular environments. *Paper 2* found that young children use core geometry to interpret highly realistic photographs and perspectival line drawings of scenes and objects just as they do to interpret less iconic overhead maps. *Paper 3* showed that young children automatically engage these core geometries during spatial symbol reading and suggested that they cannot combine extended surface information and object information even when their success depends on it. The concluding chapter suggested that older children's use of spatial symbols begins to relate distance information relevant for navigation with relative length and angle information relevant for form analysis through development and that this integration reflects a capacity for reasoning about the abstract concepts of formal geometry. The final chapter also suggested that our core systems of geometry may have even shaped our cultural development through historical time. While our system for form analysis, which represents the geometry of objects and visual forms, preserves information necessary to produce a 2D drawing, our system for navigation, which represents the geometry of scenes, does not. Our resulting difficulty translating scene-relevant geometry to a 2D drawing may explain the protracted emergence of landscapes in the history of art.

The totality of this research program seeks to elucidate a mystery that has engaged thinkers from Plato to Descartes to Husserl: How is it possible that humans can conceive of the points and lines of formal geometry despite only experiencing the scenes and objects of everyday life? It begins, I hope, a sustained contribution, however small, to our understanding of how we come to know both the material world in which we live and the abstract world in which we think.

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