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Analogical Processes in Children's Understanding of Spatial Representations

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We propose that map reading can be construed as a form of analogical mapping. We tested 2 predictions that follow from this claim: First, young children's patterns of performance in map reading tasks should parallel those found in analogical mapping tasks; and, second, children will benefit from *guided alignment* instructions that help them see the relational correspondences between the map and the space. In 4 experiments, 3-year-olds completed a map reading task in which they were asked to find hidden objects in a miniature room, using a corresponding map. We manipulated the availability of guided alignment (showing children the analogical mapping between maps and spaces; Experiments 1, 2, and 3a), the format of guided alignment (gesture or relational language; Experiment 2), and the iconicity of maps (Experiments 3a and 3b). We found that (a) young children's difficulties in map reading follow from known patterns of analogical development—for example, focusing on object similarity over relational similarity; and (b) guided alignment based on analogical reasoning led to substantially better performance. Results also indicated that children's map reading performance was affected by the format of guided alignment, the iconicity of the maps, and the order of tasks. The results bear on the developmental mechanisms underlying young children's learning of spatial representations and also suggest ways to support this learning.

Keywords: analogy, symbol, iconicity, map reading, developmental

An important characteristic of human spatial cognition is the ability to create and use spatial representations (Bluestein & Acredolo, 1979; Liben & Downs, 1989, 1993). External representations such as maps and models allow us to acquire spatial information beyond the boundaries of our personal experiences and substantially augment the capacities of our spatial cognition (Liben, 2009; Uttal, 2000; Wood & Fels, 1992). However, studies have shown that young children are often unable to use spatial representations, such as maps and scale models, to locate hidden objects in a corresponding space (Blades & Cooke, 1994; DeLoache, 1987, 1989; DeLoache, Kolstad, & Anderson, 1991; but see Huttenlocher, Newcombe, & Vasilyeva, 1999; Shusterman, Lee, & Spelke, 2008; Winkler-Rhoades, Carey, & Spelke, 2013). Even some adults have difficulty using maps to navigate in unfamiliar environments (Liben, 2009). It is therefore important to understand how the ability to comprehend maps and other spatial representations emerges during development.

Spatial representations, such as maps, use the spatial relationships among perceptual symbols to represent the spatial relationships among physical places in the corresponding environment (DeLoache, 1989; Liben, 1999; Plumert & Nichols-Whitehead, 2007; Vosmik & Presson, 2004). For example, two black dots on a map of the United States can stand for New York and Chicago, as long as the relative spatial relation between these two cities is preserved on the map, even though these dots share no *object similarity* with the real cities. Even the actual distance between two cities on a map does not match the distance in the referent space; however, what matters is that the relative distance is preserved: If Chicago is twice as far from a third city as is New York in the space, then the same relative distance will be true in the map. In other words, the essential resemblance between a map and its referent space is in the *relational similarity* between the spatial structure of the map and that of the space (Gattis, 2002). However, young children often do not appreciate this fundamental characteristic of spatial representations, instead relying on object similarity when drawing connections between spatial symbols and their referents. Research on children's map reading has shown that children initially focus on the object similarity between maps and spaces, even though most maps involve the use of noniconic symbols—representations that do not directly resemble their referent spaces (Werner & Kaplan, 1963). For instance, Liben and Downs (1989) asked children to identify features on maps or aerial photographs of geographic areas (e.g., a map of Pennsylvania or an aerial photograph of Chicago). They found that children often focused on object matches: For example, one child claimed that a line on a map could not represent a road, because the line was too narrow to accommodate a car. Hence, a critical conceptual leap that children have to achieve in understanding maps and other spatial representations is to shift focus from object similarity to relational similarity. It is thus important to understand when and how children can use these different kinds of similarities to establish correspondences between spatial representations and spaces (Loewenstein & Gentner, 2001).

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In this work, we adopt the theoretical framework of analogical mapping to explain how children establish different kinds of correspondences between maps and their referents. We propose that map reading involves a process of analogical reasoning, during which a map-reader aligns the relative spatial structure of the map with the relative spatial structure of the space. If so, then applying theory and research on the development of analogical comparison can shed light on when and how young children connect (or fail to connect) maps with their referent spaces; this approach can also suggest ways to support children's map learning. Thus, our chief hypothesis is that analogical processes are centrally involved in connecting a map with its referent space. Two sets of predictions follow from this general hypothesis. First, we would expect the development of map reading to show the same patterns as in the development of analogical mapping more generally. Second, we would expect that guiding children to establish a relational alignment between maps and spaces should improve their understanding of maps. We next review analogical development, and then turn to the idea of guided alignment.

Analogical Development

Research on the development of analogy and similarity has revealed that children initially rely on object similarity to establish correspondences and only gradually start to appreciate relational similarity (Gentner & Rattermann, 1991; Gentner & Toupin, 1986; Richland, Morrison, & Holyoak, 2006). Although young children[1]—even 3-year-olds—can show sensitivity to relational information in some contexts (Loewenstein & Gentner, 2001; Marzolf, DeLoache, & Kolstad, 1999), this ability is fragile and is strongly influenced by whether there are also object matches. In general, research on young children's relational reasoning shows a developmental pattern that gradually changes from relying on object similarity to appreciating relational similarity, a phenomenon that has been termed the *relational shift* (Gentner, 1983; Gentner & Medina, 1998). Further, children who can succeed in a relational mapping under ideal circumstances often fail when there are inconsistent object matches (Gentner & Rattermann, 1991; Gentner & Toupin, 1986; Paik & Mix, 2006; Richland et al., 2006).

This early reliance on object matches manifests itself in three ways: the *overall similarity* effect, the *cross-mapping* effect, and the *progressive alignment* effect. Both of the first two effects can be seen in a story-mapping task conducted by Gentner and Toupin (1986). Six- and 9-year-old children were told a story and acted it out with stuffed animals. They were then asked to retell the story with new animals, which varied in similarity to the first three. Both age groups were highly accurate in the *overall similarity* condition, in which the new characters resembled the corresponding initial characters (e.g., the initial "hero" was a goose and the new one was a swan). Their performance was worse when the three new animals were totally dissimilar from the first set. But the worst performance was in the *cross-mapping* condition, in which similar objects occupied different relational roles: for example, goose ≥ raccoon, panda ≥ monkey, and chimpanzee ≥ swan. In a cross-mapping task, object similarity and relational similarity are pitted against each other, so if children rely on object matches to establish correspondences, they would perform poorly in this condition. As predicted, younger children performed extremely poorly in the cross-mapping condition; they were unable to set aside object similarity and attend to the plot structure. Older children were better able to achieve a relational mapping despite the competing object matches.

This study illustrates a general point about analogical development: Early in learning, children's performance benefits from having similar objects in similar roles, and is harmed by having similar objects in different relational roles (cross-mapping). These patterns are also seen in perceptual analogy tasks. For example, Gentner and Rattermann (1991) gave 3-, 4-, and 5-year-olds a perceptual analogy task (see Figure 1) in which the experimenter and the child each had a set of three objects, arranged in order of size (e.g., large, medium, and small clay pots). Children watched the experimenter hide a sticker under one of the objects in her set; then, they searched for their own sticker, which was always hidden under the relationally corresponding object (i.e., the object with the same relative size). Three-year-olds succeeded when identical objects occupied the same relational roles (Figure 1, bottom row), but performed poorly in the cross-mapping condition (Figure 1, top row), in which identical objects occupied different relational roles. Despite being shown the correct answer after every trial, children often chose on the basis of object similarity, rather than mapping on the basis of relational role (relative size). As predicted by the relational shift hypothesis, 4- and 5-year-olds were better able to map on the basis of relational similarity. However, when 3-year-olds were invited to think about the *decreasing size* relational pattern within each set (by describing both sets as "Daddy, Mommy, Baby"), their performance was dramatically better (Rattermann & Gentner, 1998)—evidence for the importance of relational knowledge in bringing about the relational shift.

The third important pattern concerning children's early reliance on object matches in relational thinking is *progressive alignment* (Kotovsky & Gentner, 1996). This refers to the phenomenon whereby children who carry out an overall similarity match (in which object similarity supports the relational alignment) are then better able to succeed on a purely relational match with the same underlying structure than children who have not had this experience (Goldstone & Son, 2005; Haryu, Imai, & Okada, 2011; Kotovsky & Gentner, 1996; Loewenstein & Gentner, 2001). For example, Kotovsky and Gentner (1996) found that children who first compared patterns that were symmetric on the same dimension, such as size (as in ○◯○ and ■■■), subsequently performed better on less similar examples of symmetry, such as a cross-dimensional match between size symmetry and color symmetry (as in ○◯○ and ■□■). This suggests that the close comparisons, which are easy to align, can render the common relational structure more salient, making it easier to perceive that common structure in more dissimilar examples.

Guided Alignment

Our second set of predictions is that helping children to establish a relational alignment between maps and spaces can support their

[1] The ability to abstract a common relational pattern from a series of alignable examples is present even in 7- to 9-month-old infants (Ferry, Hespos, & Gentner, 2015); however, only much later are children able to carry out a relational mapping between pairs of items without prior opportunity to abstract the relation from multiple alignable examples.

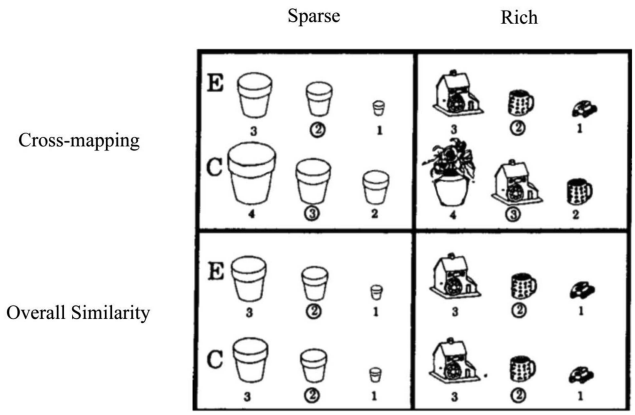

Figure 1. Stimulus sets used in Gentner and Rattermann (1991). The numbers indicate identical objects; the circle shows the correct mapping, given that the experimenter had chosen the middle object. Adapted from "Language and the Career of Similarity (p. 246)," by D. Gentner and M. J. Rattermann, 1991, in S. A. Gelman & J. P. Byrnes (Eds.), *Perspectives on language and thought: Interrelations in development* (pp. 225–277), New York, NY: Cambridge University Press.

understanding of maps. Previous research has shown that young children have considerable difficulty in interpreting maps. For example, children often do not spontaneously rotate maps that are misaligned with their referent spaces (Vosmik & Presson, 2004), even though they find it difficult to interpret misaligned maps (Bluestein & Acredolo, 1979; Liben & Yekel, 1996; Uttal, Gregg, Tan, Chamberlin, & Sines, 2001), suggesting that they may not understand the need to establish correspondences between the map and the space. Even when a map is physically aligned with the referent space, young children may fail to establish alignment on the basis of common spatial relations (Liben, 1999; Liben & Downs, 1993; see also Blades & Cooke, 1994; DeLoache, 1987, 1989).

However, research has shown that children can benefit from adults' guidance in these kinds of complex learning situations (Honomichl & Chen, 2006, 2012). Thus, in the current study, we designed a novel intervention—*guided alignment*—to help children carry out the analogy between maps and space. According to the structure-mapping theory (Forbus, Ferguson, Lovett, & Gentner, 2016; Gentner, 1983; Gentner & Markman, 1997), two key characteristics of analogical mapping are (a) *one-to-one correspondence* between the elements of the two analogs, and (b) *parallel relational structure* between the two representations. This suggests two ways to support the alignment between maps and spaces: (a) by showing the correspondences between symbols in the map and objects in the space, and (b) by showing the parallel relational structure between the map and the space. In the studies that follow, we explore ways to use gesture and language to achieve these two aims (see Table 1).

To help children establish correspondences between the map and space, we used gestures in Experiments 1 and 3a and language in Experiment 2. Prior research suggests that the effective use of gesture can facilitate relational reasoning. For example, Richland, Zur, and Holyoak (2007) provided correlational evidence that gesture can be effective in promoting understanding of analogies. They analyzed videotapes of math classes from the United States, Hong Kong, and Japan, and found that differences in the degree to which teachers used gestures and other means of clarifying the correspondences between analogous math problems were predictive of students' performance. In particular, teachers often use gestures (e.g., pointing) to link related ideas in classroom instructions (Alibali et al., 2014). Research has suggested that this type of linking gesture can provide visual cues to help learners see the connection between two analogs (Alibali et al., 2014; Richland & McDonough, 2010; Richland & Simms, 2015). Thus, the current study deployed a type of gesture that we will call a *correspondence gesture*—pointing back and forth between the corresponding elements within the analogs to highlight the correspondences. Another way to help children establish analogical correspondences is through language (Gentner, Anggoro, & Klibanoff, 2011; Rattermann & Gentner, 1998)—for example, by using the same term for the map symbol (e.g., "road") as for the referent object.

The second aspect of analogical mapping is establishing parallel relational structure. Here, too, language can be helpful in guiding children. There is considerable evidence that relational language can help children notice and encode spatial relations (Casasola, 2005; Gentner, Özyürek, Gürcanli, & Goldin-Meadow, 2013; Hermer-Vazquez, Spelke, & Katsnelson, 1999; Loewenstein & Gentner, 2005; Son & Goldstone, 2010; see Gentner & Christie, 2010, for a review). For example, in the Gentner and Rattermann's (1991) perceptual analogy task discussed earlier, 3-year-olds performed far better on a challenging mapping task when each set was described in the same relational language—"Daddy, Mommy, Baby." It seems likely that this language conferred two benefits. First, as discussed above, hearing the same term (e.g., "Daddy") for objects in both sets may have helped children establish object correspondences. Second, applying the familiar relational pattern

Table 1
Guided Structural Alignment: Techniques for Fostering Parallel Relational Structure and One-to-One Correspondence Across the Three Studies

Experiment	Conditions	One-to-one correspondence	Parallel relational structure
E1	Guided alignment	Correspondence gestures	"Between"
		"First, second, third"	"First, second, third"
	Control	None	None
E2	Gesture	Correspondence gestures	Relational gestures
	Language	"First, second, third"	"Between"; "First, second, third"
E3a	Guided alignment	Correspondence gestures	Relational gestures
	Control	None	None

("Daddy, Mommy, Baby") might have helped children encode the parallel relational structure of decreasing size.

Gesture is another symbolic tool that has been shown to help children focus on a relational pattern within a single representation (Novack, Congdon, Hemani-Lopez, & Goldin-Meadow, 2014). For example, Goldin-Meadow, Cook, and Mitchell (2009) helped elementary school students to solve mathematical equivalence problems by using an abstract gesture (producing a V-point gesture to the two numbers on the left side of an equation followed by a point at the blank on the right side). This abstract gesture highlighted the critical relational structure embedded in the problems to children, leading to better performance on the tasks. Studies have also shown that adults can use newly learned relational gestures to infer the meaning of novel relational gestures (Gattis, 2004). In the current studies, we tested whether using parallel relational gesture in map and space can serve to highlight their common spatial structure.

Current Study

Our chief hypothesis is that analogical processes are centrally involved in children's understanding of maps. In Experiment 1, we tested two predictions that follow from this central hypothesis. First, early in learning, children should focus strongly on objects, and therefore they should have great difficulty when the object matches between the map and the space are inconsistent with the relational alignment (i.e., cross-mapping) compared with the case when the object matches are consistent with the relational alignment. Second, children's map understanding can be improved by guiding them through the analogical mapping between the map and the space. To test these predictions, in Experiment 1, we gave children maps varying in predicted difficulty and varied whether the children received guided-alignment training. In subsequent studies, we also asked what kinds of gestural and linguistic support were most effective for this purpose, across maps of different levels of iconicity.

Experiment 1

Method

We gave children two different mapping tasks varying in difficulty. Both tasks were intended to be somewhat challenging, to permit testing the efficacy of guided alignment. In the first task (identical-items task), we used iconic map symbols that resembled their referents in the space (Figure 2, Set A1). All three objects in the room were alike (and hence the three map symbols were also identical to each other). If we had used three distinctive objects and their iconic symbols, children could have relied on object similarity to draw correspondences (Blades & Cooke, 1994). Thus, our design allowed us to determine whether children could connect the maps and spaces on the basis of relational similarity. In the second task (cross-mapping task), the elements on the map were cross-mapped with those in the room; that is, each element on the map resembled a noncorresponding object in the room (Figure 2, Set A2). To minimize the influence of other factors (e.g., scaling, rotation) on children's understanding, we used maps of the same size as their referent environment (miniature rooms) and presented maps and rooms physically aligned. Children were asked to search for hidden objects in the room after the experimenter showed their locations on the map.

The second factor in this study was guided alignment. We contrasted a *guided alignment group*, which received guided alignment based on correspondence gestures and relational language, with a *control group* that received the same mapping task without

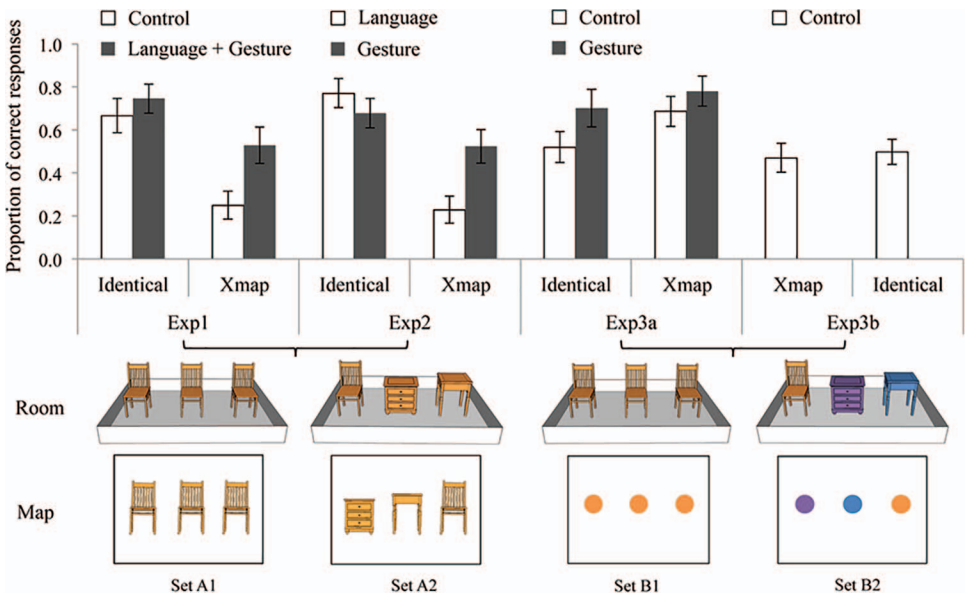

Figure 2. Proportion of correct responses for the identical-items task and the cross-mapping task across all experiments, with their corresponding room and map (Sets A1 and A2 were for Experiments 1 and 2; Sets B1 and B2 were for Experiment 3a and 3b). Exp = experiment; Identical = identical-items task; Xmap = cross-mapping task.

this intervention. Table 1 shows how different interventions were used to foster one-to-one correspondence and parallel relational structure. Both groups were given the same two tasks, in the same order: the identical-items task followed by the cross-mapping task.[2] We hypothesized that children in the guided-alignment condition would perform better in the search tasks than those in the control condition. Thus, the design was 2 (condition, between-subject) × 2 (task, within-subject).

In the guided-alignment condition, we aimed to convey two essential properties of analogical mapping: one-to-one correspondences between map elements and space elements, and parallel relational structure (see Table 1). To convey the correspondences, we used back-and-forth gestures, as illustrated below. To convey the parallel relational structure in map and space, we used relational language. Our choice of relational language was based on several considerations. We did not use spatial terms such as *left* and *right* to convey the left-middle-right spatial pattern, because the correct use of *left* and *right* does not emerge until about 7 years of age (Clark & Klonoff, 1990; Craton, Elicker, Plumert, & Pick, 1990; Rigal, 1994; Shusterman et al., 2008). Instead, we used the spatial term *between*, which denotes the spatial relationship between a target object and two referents. Although only a few studies have investigated children's understanding of the term "between," there is some evidence suggesting that 3-year-olds can identify target objects upon hearing descriptions using the word "between" (Durkin, 1983; Foster & Hund, 2012; Simms & Gentner, 2008; Washington & Naremore, 1978). We also used the numeral terms *first*, *second*, and *third* to convey the left-middle-right order of elements in the map and the room. There is evidence that 3-year-old children know the count list at least as far as 1, 2, 3 (Carey, 1998; Fuson, 1988; Wynn, 1990), and that they can apply this ordinal structure to a spatial array (Gentner & Christie, 2006). Miller, Marcovitch, Boseovski, and Lewkowicz (2015) recently showed that young children can use ordinal terms (first, second, third) to encode locations in a spatial memory task, although performance was better using labels that emphasized feature information (e.g., color). Even though studies have suggested that children do not have to fully understand the meaning of spatial terms to utilize the relational structures they convey in encoding spatial relations (Dessalegn & Landau, 2008), we caution that preschoolers are still in the process of acquiring many relational terms, which may limit the effectiveness of relational language in conveying spatial structures.

Participants. The participants were 35 preschool children (16 boys and 19 girls), with an average age of 38 months (range = 35–43 months). Children were randomly assigned to either the guided-alignment condition (n = 17; male = 7) or the control condition (n = 18; male = 9). A prior power analysis was conducted using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007), suggesting that a sample size of 30 participants is adequate to achieve 80% power with a medium effect size.

Materials. The study took place in a laboratory designed for testing young children. Children sat on a chair in front of a small table on which the miniature rooms and maps were presented. The experimenter sat on the diagonal side of the table and always gave instructions from the perspective of the child. Two miniature rooms and their corresponding maps were used (see Figure 2): Room A1 for the identical-items task and Room A2 for the cross-mapping task. The rooms were made from foam core board with a dimension of 12 in. × 12 in., and a height of 1 in. Three identical chairs were placed in Room A1, each roughly 3 in. tall and 2 in. wide. The corresponding map for Room A1 was roughly the same size as the room (12 in. × 12 in.), with three identical chairs as well. The chairs on the map, made from photographs of the chairs in Room A1, were the same color and size as the real chairs in the room. In Room A2, there were three pieces of furniture from different categories—a chair, a nightstand, and a table. The furniture was roughly 3 in. tall and 2 in. wide. The spatial locations of these three pieces of furniture were mismatched with their identities between Room A2 and its corresponding map. Specifically, on the map of Room A2, the three pieces of furniture from left to right were nightstand, table, and chair, whereas the order in the room was chair, nightstand, and table (see Figure 2). Two magnetic sheets were cut to resemble the shape of bones, and six other magnetic sheets were glued at the bottom of all pieces of furniture to provide hiding locations. A stuffed dog was used to introduce the background story.

Procedure.

Orientation. An experimenter introduced a stuffed dog to the child and told the child that the doggie liked to hide his bones underneath the furniture in the room. She then invited the child to play a hide-and-find game—she would show them on the map where the doggie had hidden his bone, and the child would help to find the bone in the room.

Learning phase. Children in the guided-alignment group learned about the maps of the rooms (both Room A1 and Room A2) through guided alignment, whereas the control group did not.

Guided-alignment condition. The experimenter first introduced Room A1[3] to the children using ordered numerical language ("first, second, third"). Specifically, the experimenter said, "There are three chairs in the room—the first chair, the second chair, and the third chair," while pointing to each of them in sequence. The experimenter then invited children to examine the bottom of each chair by saying, "Let's look at the first (second/third) chair—does it have a bone underneath it?" After this, the experimenter introduced the map, by saying, "There are three chairs on the map, too—the first map chair, the second map chair, and the third map chair," while pointing to each of them in sequence (see Figure 3 for an illustration of these and other procedures, and the Appendix for all instructions).

[2] In the first three studies, the identical-items task (which was predicted to be easier) preceded the cross-mapping task (which was predicted to be difficult). This was done to allow testing the prediction that the cross-mapping task would be more difficult than the identical-items task. Because the two tasks involve the same relational mapping, the second task should be boosted by progressive alignment. Thus, had the identical-items task come second, any advantage found for this task over the cross-mapping task would have been uninterpretable—it could stem from the inherent difficulty of the tasks, or from their order in the sequence. By placing the cross-mapping task second (so that it gains the advantage of progressive alignment), we can interpret a decrement in performance from identical-items to cross-mapping as evidence for the greater difficulty of cross-mapping over identical-items.

[3] In this and all other studies, we first introduced the room with its three items, and then the map with its three symbols. After that, in giving the more detailed connections between the map and the room, we always began with the map. This was done in order to better fit the child's (later) task, which was to project from the map to the room.

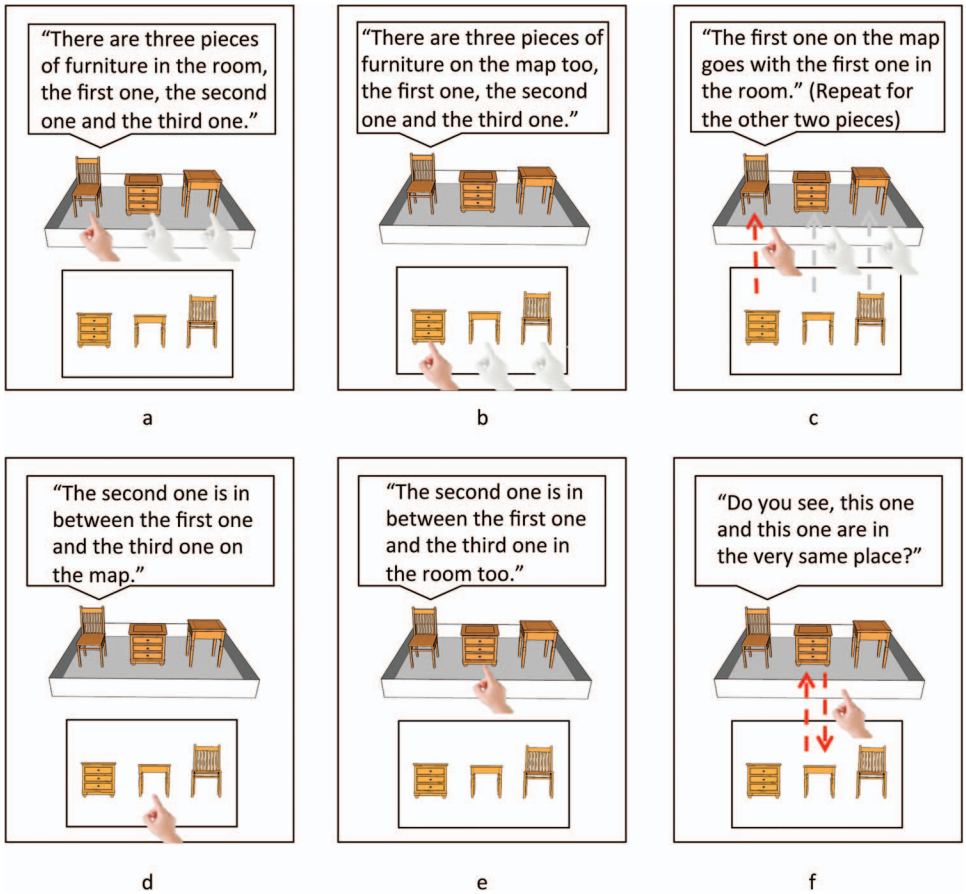

Figure 3. A schematic illustration of the instructions for children in the guided-alignment condition in Experiment 1 (following the sequence of a–f). Verbal instructions are quoted in the textbox. A single hand indicates pointing gesture. A one-way arrow indicates pointing to two items involved in a sequence once. Two-way arrows indicate pointing to two items back-and-forth several times. Degraded hands indicate sequential gestures. We illustrate the procedures using the cross-mapping task, but the same procedures were used in the identical-items task. See the online article for the color version of this figure.

Next, the experimenter used a combination of back-and-forth correspondence gestures and relational language to show the one-to-one correspondence and parallel relational structure between the map and the room (see Table 1). For example, the experimenter said, "The first (second/third) map chair goes with the first (second/third) chair in the room," while pointing to each of them in sequence. The experimenter also used the relational term "between" to further show the parallel spatial structure between the map and the room. Specifically, the experimenter said, "The second map chair is in between the first map chair and the third map chair on the map, and the second chair is in between the first chair and the third chair in the room, too," while pointing and gesturing to the respective spaces. To show the one-to-one correspondences, the experimenter then used back-and-forth correspondence gestures: "Do you see, this chair [pointing to the middle chair on the map] and this chair [pointing to the middle chair in the room] are in the very same place?" [pointing back-and-forth]. To make sure that children understood the instructions, the experimenter then asked, "Where does this one go in the room?" for two of the items (first and third map chair). The experimenter corrected children no more than three times if they answered incorrectly. Only one child failed.

Control condition. The experimenter introduced the room by saying, "There are three chairs in this room—here, here, and here," while pointing to each of them. As in the guided-alignment condition, the experimenter invited children to examine each chair to see if there was a bone underneath. The experimenter then introduced the map of the room by saying, "There are three chairs on the map, too, here, here and here. The map looks just like the room." Although the experimenter did not point out the structural alignment between the map and the room, they were always physically aligned in front of the children (see Figure 4).

Test phase. The experimenter showed children where a bone was on the map and asked them to search for the bone in the room by saying, "Remember they are always hidden in the same places." Children were asked to cover their eyes while the experimenter was hiding the bone. The experimenter also used a curtain to prevent children from peeking. Children from both conditions were asked to complete six trials of the identical-items task. Then,

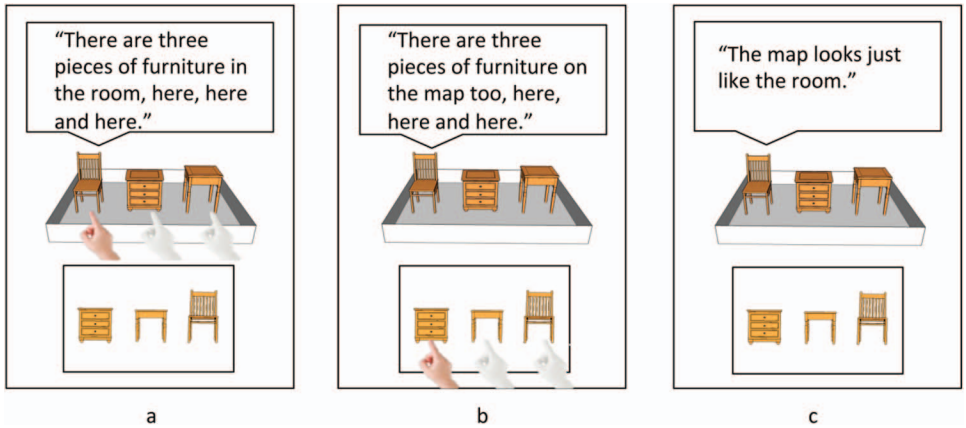

Figure 4. A schematic illustration of the instructions for children in the control condition in Experiment 1 (following the sequence of a–c). Verbal instructions are quoted in the textbox. A single hand indicates pointing gesture. Degraded hands indicate sequential gestures. See the online article for the color version of this figure.

children were introduced to Room A2 (the cross-mapped room). Both groups were given the same introduction and training as they had been given for Room A1. They then completed six trials of the cross-mapping task. Each hiding location was tested twice with a total of six trials. The order of hiding locations was counterbalanced across subjects, with the constraint that no hiding location was tested twice in a row.

Scoring. Children were scored as correct on a search trial only if they searched at the correct location on their first attempt. If children searched incorrectly, the experimenter revealed the correct location to them before moving on to the next trial. The main dependent variable was the proportion of correct responses across six search trials. During the cross-mapping task, we also coded children's *object-matching errors*. An object-matching error was scored if the child searched under the item that had the same physical appearance as the map element but occupied a different spatial position. As reviewed earlier, the relational shift hypothesis predicts that young children are likely to focus on object similarity and overlook relational correspondence, and hence are prone to object-matching errors. We predicted that children in the guided-alignment condition would make fewer object-matching errors than those in the control condition.

Results

A 2 (condition) × 2 (task) mixed repeated-measure ANOVA revealed a main effect of task, $F(1, 33) = 14.50$, $p = .001$, $\eta_p^2 = .31$ (see Figure 2). As predicted, children performed worse in the cross-mapping task ($M = 39\%$, $SD = 34\%$) than in the identical-items task ($M = 70\%$, $SD = 31\%$), consistent with the prediction that conflicting object matches would disrupt the analogical mapping between the map and room. There was also a significant main effect of condition, $F(1, 33) = 7.56$, $p = .01$, $\eta_p^2 = .19$. Overall, the guided-alignment group ($M = 64\%$, $SD = 21\%$) performed significantly better than the control group ($M = 45\%$, $SD = 18\%$). There was no interaction between condition and task, $F(1, 33) = 1.48$, $p = .23$, suggesting that support for structural alignment improved performance in both tasks.

Both the guided-alignment group and the control group performed reliably above chance level (33%) in the identical-items task, *t*s (16, 17, respectively) > 4.21, *p*s $< .002$. However, in the cross-mapping task, only the guided-alignment group ($M = 53\%$, $SD = 35\%$) performed above chance, $t(16) = 2.35$, $p = .03$; the control group ($M = 25\%$, $SD = 27\%$) failed to do so, $t(17) = 1.25$, $p = .23$. The two groups also differed in their proportion of object-matching errors, $t(33) = 2.15$, $p = .04$. The proportion of object-matching errors was above chance for the control group ($M = 64\%$, $SD = 34\%$), $t(17) = 3.81$, $p = .001$, but not for the guided-alignment group ($M = 38\%$, $SD = 36\%$), $t(16) = .6$, $p = .56$. To examine whether children were learning across trials, we compared the proportion of correct responses for the first and last three trials. Children in the control condition averaged 24% for the first three and 26% for the last three trials, $t(17) = .32$, $p = .76$; children in the guided-alignment condition averaged 49% for the first three trials and 54% for the last three trials, $t(16) = 1.29$, $p = .22$. Although neither group showed significant learning across trials, those in the guided-alignment group were able to connect the maps and spaces throughout the trials.

Discussion

Overall, the results of Experiment 1 bear out our predictions. First, the results parallel those found in analogical mapping. Children in the control group performed better with neutral identical objects than they did in the cross-mapping task; and they frequently made object-matching errors in the cross-mapping task. Our results also bear out the idea that guided alignment can foster 3-year-olds' map understanding—children in the guided-alignment condition performed significantly better than those in the control group on the cross-mapping task.

However, our guided-alignment manipulation involved a number of different facets, including the use of relational language and gestures. It is not clear which aspects of our manipulation were most effective in improving children's understanding. In Experiment 2, we sought to tease apart the effects of gesture and relational language on children's map reading.

Experiment 2

Method

We contrasted two conditions designed to support guided alignment: a gesture condition and a language condition. Both conditions included interventions designed to convey parallel relational structure and to clarify one-to-one correspondences. Thus, the purpose of Experiment 2 was to investigate how to best achieve guided alignment: whether gestural or linguistic support would be more effective for young children. Children were randomly assigned to one of the two conditions, and both groups were given the same two tasks, in the same order: the identical-items task followed by the cross-mapping task.

In the language condition (as in Experiment1), parallel relational structure was conveyed through the spatial term "between" and the numerical terms "first, second, third" (see below and Figure 5). To convey the correspondences, we used the same numerical terms ("first, second, third") in the map as in the room. That is, when the numerical terms are used as common *labels*, they should convey correspondences between the map and room. (In addition, their common numerical *order* should also convey parallel spatial relational structure.) No back-and-forth gestures were used to reinforce the object correspondences in this condition.

In the gesture condition, we used a novel arcing gesture to convey parallel relational structure between the map and the room (see below and Figure 6). As in Experiment 1, one-to-one correspondences were conveyed with back-and-forth correspondence gestures. No relational language was used in this condition.

Participants. Thirty children participated (average age = 39 months; range = 35–44 months). Children were randomly assigned to either the language condition (n = 16; male = 10) or the gesture condition (n = 14; male = 9). A prior power analysis was conducted using G*Power 3.1 (Faul et al., 2007), suggesting that a sample size of 30 participants is adequate to achieve 80% power with a medium effect size.

Materials. The materials were identical to those of Experiment 1.

Procedure. As in Experiment 1, children were invited to play a hide-and-find game, in which they used a map to find hidden objects in the room. All procedures were identical to those in Experiment 1, except for the training given to children in the two conditions.

Language condition. The experimenter introduced the room to children using ordered numerical language ("first, second,

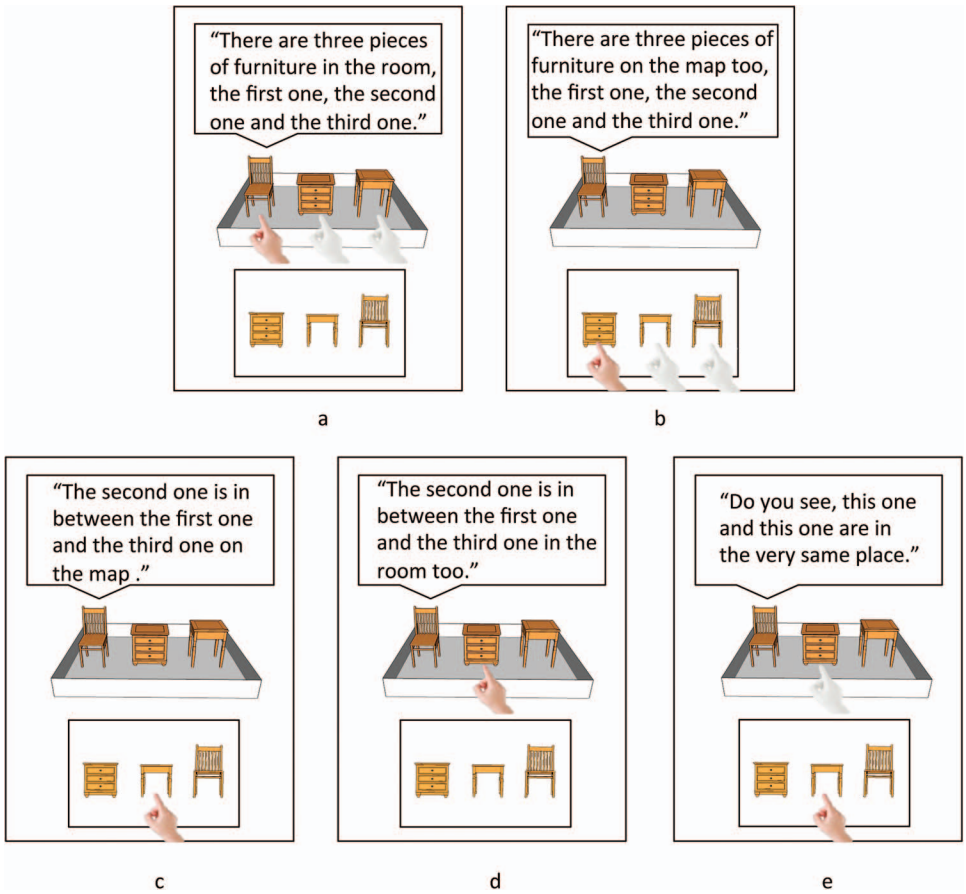

Figure 5. A schematic illustration of the instructions for children in the language condition in Experiment 2 (following the sequence of a–e). Verbal instructions are quoted in the textbox. A single hand indicates pointing gesture. Degraded hands indicate sequential gestures. See the online article for the color version of this figure.

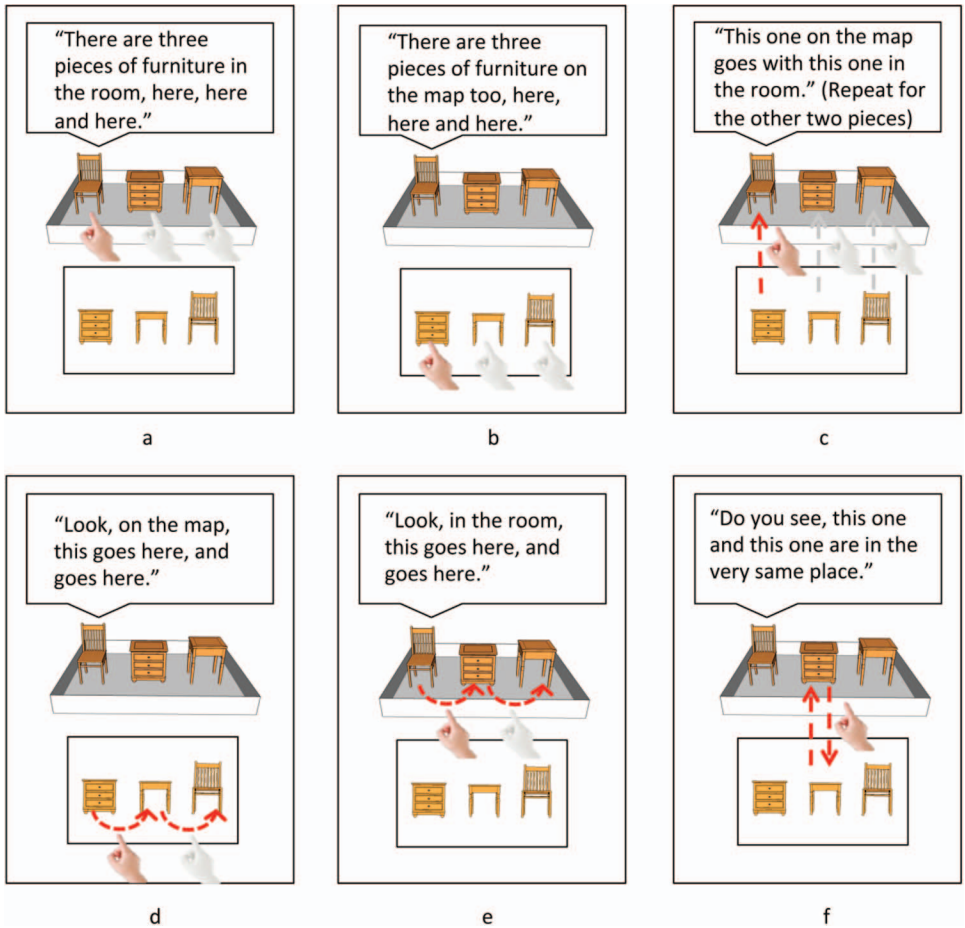

Figure 6. A schematic illustration of the instructions for children in the gesture condition in Experiment 2 (following the sequence of a–f). Verbal instructions are quoted in the textbox. A single hand indicates pointing gesture. A one-way arrow indicates pointing to two items involved in a sequence once. Two-way arrows indicate pointing to two items back-and-forth several times. Curved arrows indicate arcing gesture (pointing to each object on the map in a left–right sequence with an arcing movement between each contiguous pair of objects). Degraded hands indicate sequential gestures. See the online article for the color version of this figure.

third"): "There are three chairs in the room—the first chair, the second chair, and the third chair," while pointing to each of them (see Figure 5). As in Experiment 1, children were invited to examine the bottom of each chair to reinforce the ordinal words, "Is there a bone underneath the first/second/third chair?" The experimenter then introduced the map: "There are three chairs on the map, too—the first map chair, the second map chair, and the third map chair," while pointing to each of them. She used the spatial term "between" in both the map and the room:

> "The second map chair is in between the first map chair and the third map chair on the map. The second chair is in between the first chair and the third chair in the room, too". She then further conveyed the parallel relational structure by pointing out "Do you see, this chair [pointing to the middle chair on the map] and this chair [pointing to the middle chair in the room] are in the very same place?"

No back-and-forth gestures were used.

Gesture condition. The experimenter did not use any relational language ("first, second, and third" or "between"). She introduced the room by saying, "There are three chairs in this room—here, here, and here," while pointing to each of them. As in the language condition, children were invited to examine each chair: "Let's look at this chair. Is there a bone underneath it?" The experimenter then introduced the map: "There are three chairs on the map too—here, here and here." To show the correspondences between items on the map and those in the room, the experimenter used a correspondence gesture: "This chair [pointing to the left chair on the map] goes with this chair [pointing to the left chair in the room]." The experimenter repeated this correspondence gesture for both the middle and right chairs. Next, to convey parallel relational structure, the experimenter used identical arcing gestures to highlight the common spatial structures among the items on the map and those in the room (see Figure 6): "Look, this goes here, and goes here," while pointing to each object on the map in a left–right sequence with an arcing movement between each contiguous pair of objects. She repeated the same gestures and

instructions in the room. The experimenter then focused on the chair in the middle; while pointing back and forth, she asked, "Do you see, this chair [pointing to the middle chair on the map] and this chair [pointing to the middle chair in the room] are in the very same place?"

Results

A 2 (condition) × 2 (task) mixed repeated-measure ANOVA showed a significant main effect of task, $F(1, 28) = 32.41$, $p = .001$, $\eta_p^2 = .54$ (see Figure 2). As predicted, children performed worse on the cross-mapping task ($M = 37\%$, $SD = 30\%$) than on the identical-items task ($M = 72\%$, $SD = 26\%$). There was no main effect of condition, $F(1, 28) = 1.71$, $p = .20$. However, there was a significant interaction between condition and task, $F(1, 28) = 10.08$, $p = .004$, $\eta_p^2 = .27$. Planned comparisons showed that on the identical-items task, there was no significant difference between children in the language condition ($M = 77\%$, $SD = 27\%$) and the gesture condition ($M = 68\%$, $SD = 26\%$), $t(28) = .97$, $p = .34$. However, a significant difference emerged on the cross-mapping task, $t(28) = 2.97$, $p = .006$: The gesture group chose the correct location on 52% of the trials ($SD = 29\%$), whereas children in the language condition chose the correct location on only 23% of the trials ($SD = 25\%$).

Both the gesture group and the language group performed reliably above chance levels (33%) in the identical-items task, *t*s (13, 15, respectively) > 5.04, *p*s < .001. However, only the gesture group performed above chance on the cross-mapping task, $t(13) = 2.48$, $p = .03$. The two groups also differed in their proportion of object-matching errors, $t(28) = 2.13$, $p = .04$. The proportion of object-matching errors among children in the gesture condition ($M = 34\%$, $SD = 27\%$) did not differ from chance, $t(13) = .22$, $p = .83$. In contrast, children in the language condition ($M = 56\%$, $SD = 29\%$) made significantly more object-matching errors than expected by chance (33%), $t(15) = 3.14$, $p = .007$. This pattern suggests that guided alignment based on gestures was more helpful in the difficult cross-mapping task than that based on language. This fact that gesture was more helpful than language might simply mean that children are not sufficiently familiar with the relational language used here. However, it could also have resulted from the spatial nature of gesture; gesture may be particularly well suited for helping children understand similar spatial relational structures.

Experiment 3a

Method

In Experiments 1 and 2, we examined the influence of guided alignment on 3-year-olds' map reading using maps with highly iconic symbols. In Experiment 3a, we asked how these techniques would apply to more typical maps, in which the elements on the map do not closely resemble the items in the referent space. To do so, we gave children abstract maps with dots indicating spatial locations. There were two versions of the task, parallel to the two tasks in the prior studies. In the identical-items task, all the objects in the room were identical and all the dots in the map were identical. In the cross-mapping task, the objects in the room were distinctive in shape and color, and the three dots in the map were of the same three colors as the items in the room, but arranged in noncorresponding order[4] (see Figure 2).

This set of materials allows us to test a further prediction of the analogical processing account of map understanding—that the difficulty of the cross-mapping task should be greater for maps with iconic symbols than those with abstract symbols. This means that the advantage of the identical-items task over the cross-mapping task should be reduced in Experiment 3a (in which the map icons were dots) compared with Experiments 1 and 2 (in which the map icons were photographs that closely matched objects in the room).

As in the prior studies, there were two groups: a guided-alignment group and a control group. Because of the effectiveness of the gesture condition in Experiment 2, we used this same technique in the guided-alignment condition of Experiment 3a.

Participants. Thirty-four children participated in the study (average age = 38 months; range = 34–42 months). Children were randomly assigned to either the guided-alignment condition ($n = 17$; male = 9) or the control condition ($n = 17$; male = 9). A prior power analysis was conducted using G*Power 3.1 (Faul et al., 2007), suggesting that a sample size of 30 participants is adequate to achieve 80% power with a medium effect size.

Materials. The hiding rooms were identical to those of Experiment 1; however, instead of iconic photographs, the maps contained colored dots. In the identical-items task, the colors of the dots in the map were all identical, as were the colors of the chairs in the room. In the cross-mapping task, the colors of the dots (blue, purple, and yellow) and those of the furniture were cross-mapped—items of the same color occupied different locations in the map and the room (see Figure 2).

Procedure. The instructions for the guided-alignment condition were the same as those in the gesture condition in Experiment 2. The instructions for the control condition were identical to the control condition in Experiment 1.

Results and Discussion

A 2 (condition) × 2 (task) mixed repeated-measure ANOVA showed a significant main effect of task, $F(1, 32) = 7.23$, $p = .01$, $\eta_p^2 = .18$ (see Figure 2). Surprisingly, in contrast to the prior studies, children performed significantly better on the cross-mapping task ($M = 73\%$, $SD = 29\%$) than on the identical-items task ($M = 60\%$, $SD = 33\%$). We speculate that performing the easier alignment task (the identical-items task) first, in combination with the use of low-iconicity symbols, helped children to succeed in the more difficult cross-mapping task. (We tested this explanation in the next experiment.)

There was no main effect of condition: The difference between the guided-alignment condition ($M = 74\%$, $SD = 29\%$) and the control condition ($M = 59\%$ $SD = 32\%$) failed to reach significance, $F(1, 32) = 2.63$, $p = .11$. The interaction between task and condition was also nonsignificant, $F(1, 32) = 1.2$, $p = .28$. Given the unexpected result that children performed better on the cross-mapping task than on the identical-items task, we conducted a

[4] As in the prior studies, we did not test the straightforward case in which the furniture items were distinctive and the colored dots were arranged in corresponding order. This was because we needed the maps to be challenging enough to allow us to test the efficacy of guided alignment.

planned comparison between the guided-alignment group and the control group on the first identical-items task only. The difference between the guided-alignment condition (M = 70%, SD = 30%) and the control condition (M = 50%, SD = 33%) was marginally significant, $t(32) = 1.87$, $p = .07$. It appears that guided-alignment training was effective in promoting children's understanding of maps with abstract symbols as well as those with iconic symbols.

To examine the effect of rich, iconic object matches on children's performance, we compared the performance of the control groups from Experiments 1 and 3a. A 2 (experiment) × 2 (task) mixed repeated-measure ANOVA revealed a marginally significant main effect of experiment, $F(1, 33) = 3.27$, $p = .08$, and a marginally significant main effect of task, $F(1, 33) = 3.01$, $p = .09$ (see Figure 7). Importantly, there was a significant interaction between experiment and task, $F(1, 33) = 18.73$, $p = .001$, $\eta_p^2 = .36$. When the map symbols were iconic (Experiment 1), children performed better on the identical-items task (M = 67%, SD = 34%) than on the cross-mapping task (M = 25%, SD = 28%), $t(17) = 3.53$, $p = .003$. However, when the map symbols were abstract (Experiment 3a), children performed better on the cross-mapping task (M = 69%, SD = 29%) than on the identical-items task (M = 50%, SD = 33%), $t(16) = 2.66$, $p = .017$.

Although not specifically predicted, this result fits with prior findings on analogical mapping. Having rich, iconic object matches *improves* performance when the local matches are consistent with the relational alignment, but *harms* performance in a cross-mapping task, when the local matches are inconsistent with the relational alignment (Gentner & Rattermann, 1991; Gentner & Toupin, 1986; Kaminski & Sloutsky, 2013; Loewenstein & Gentner, 2001; Richland et al., 2006). In Experiment 3b, we tested this possibility.

Experiment 3b

Method

The results of Experiment 3a contrast strongly with those of the first two studies, in that children performed better on the cross-mapping task than on the identical-items task. Applying known patterns from research on analogical processes leads us to consider two factors that may have led to this finding. First, the effect of cross-mapping should be lower in Experiment 3a, because the map symbols were low in iconicity, in contrast to the rich, iconic symbols used in Experiments 1 and 2. Second, children in Experiment 3a may have benefited from receiving the identical-items task first. Many studies (Goldstone & Son, 2005; Haryu et al., 2011; Kotovsky & Gentner, 1996; McNeil & Fyfe, 2012) have found that learners often perform better on a difficult analogical mapping after performing an easier mapping with the same kind of relational structure—a phenomenon referred to as *progressive* alignment[5] (Gentner, 2003; Kotovsky & Gentner, 1996). Thus, children's performance on the second task (cross-mapping) in Experiment 3a might have benefited from the easier alignment on the first task (identical-items), because the task order permitted a progressive alignment from easy to abstract mapping. If so, then performance on the cross-mapping task should suffer if children receive this task first, without the aid of a prior easier alignment task. We tested this hypothesis in Experiment 3b by switching the order of the tasks, presenting the cross-mapping task first and the identical-items task second. Two predictions follow from our hypothesis: (a) Performance on the cross-mapping task should be worse in Experiment 3b than in Experiment 3a, and (2) there would be no increase in performance from the first to the second task in Experiment 3b—in contrast to Experiment 3a; that is, we expected to see an interaction between task and experiment.

Participants. Seventeen children (male = 9) participated in the study (average age = 39 months, range = 35–42 months).

Materials and procedures. The materials and procedures were identical to those in the control condition in Experiment 3a, except that the cross-mapping task was presented before the identical-items task.

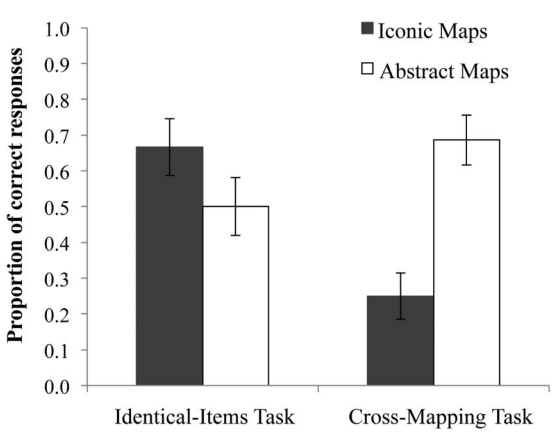

Figure 7. Proportion of correct responses in the identical-items task and the cross-mapping task for the control conditions from Experiments 1 (iconic maps) and 3a (abstract maps).

Results

A cross-experiment (Experiment 3a control condition vs. Experiment 3b) analysis was conducted to test the progressive alignment hypothesis—we expected to see an interaction between task (identical-items vs. cross-mapping) and task order (Experiment 3a vs. Experiment 3b). A 2 (task) × 2 (experiment) mixed repeated-measure ANOVA showed no main effect of experiment, $F(1, 32) = 1.53$, $p = .23$, but a marginally significant main effect of task, $F(1, 32) = 3.44$, $p = .07$ (see Figure 8). Importantly, as predicted, there was a significant interaction between experiment and task, $F(1, 32) = 6.03$, $p = .02$, $\eta^2 = 0.16$.

Planned comparisons revealed the following: Children from Experiment 3a (M = 69%, SD = 29%) performed significantly better than their counterparts from Experiment 3b (M = 47%, SD = 28%) on the cross-mapping task, $t(32) = 2.33$, $p = .03$; however, there was no significant difference in children's performance on the identical-items task between Experiments 3a (M = 50%, SD = 33%) and 3b (M = 50%, SD = 24%), $t(32) < 0.01$, $p = 1$. These results are consistent with the progressive alignment prediction derived from the structure-mapping theory: Carrying

[5] As discussed earlier, the same reasoning applies in Experiments 1 and 2, but in those studies, the progressive alignment advantage for the second (cross-mapping) task was outweighed by the difficulty of the cross-mapping task with iconic symbols.

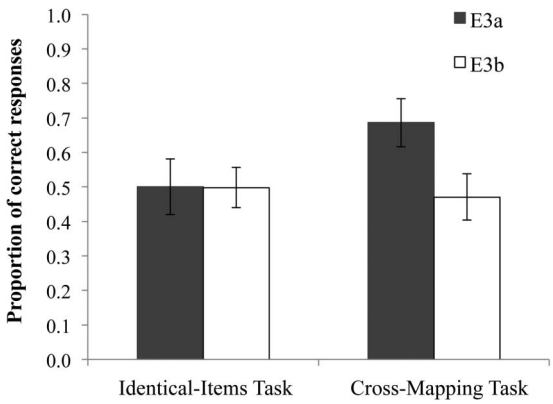

Figure 8. Proportion of correct responses in the identical-items task and the cross-mapping task for the control conditions from Experiments 3a and 3b. E3a = experiment 3a; E3b = experiment 3b.

out a relatively easy alignment task can allow a child to see the common relational structure, and this can potentiate subsequent performance on a more difficult alignment task. No such advantage is predicted for the reverse order.

General Discussion

We hypothesized that map reading involves analogical processing—that is, map reading involves a process of relational alignment and inference between the map and the space. In four experiments, we tested predictions that follow from this central hypothesis. The first line of prediction is that the development of map understanding would show patterns similar to those of analogical development in general. Prior work on analogical development shows that early in learning, children focus on object similarity, and only later come to appreciate relational similarity. If map understanding follows the same pattern, young children should perform better when the local object similarities between the map and the space are consistent with the relational alignment (as in the identical-items task) than when they are inconsistent (as in the cross-mapping task). This prediction was borne out in Experiments 1 and 2: In both studies, children performed better on the identical-items task than on the cross-mapping task, even though the cross-mapping task came second, and might have benefitted from the prior task.

A second prediction derived from analogical development is that (especially for young learners) rich object matches should improve performance when the object matches are consistent with the relational alignment, but should harm performance when the object matches are inconsistent with the relational alignment (as in a cross-mapping task). This prediction was tested through a cross-experiment comparison between the control groups from Experiments 1 and 3a. Consistent with the analogical mapping account, children performed better on the identical-items task than on the cross-mapping task when the maps were iconic (Experiment 1), but the reverse occurred when the maps were abstract (Experiment 3a).

A third prediction concerns progressive alignment—performing easily aligned analogies facilitates later understanding of more challenging analogies that have the same relational structure (Gentner, 2003; Kotovsky & Gentner, 1996). If children's map reading follows the same principle, they should perform better on a difficult mapping task when they first experience an easier mapping task than when they receive the difficult task first. This prediction was borne out in the contrast between Experiments 3a and 3b. Children's performance on the cross-mapping task was far better when it was presented *after* the easier identical-items task (Experiment 3a) than when it was presented before the identical-items task (Experiment 3b). Consistent with the principle of progressive alignment, this pattern suggests that carrying out the easy identical-items match involved an alignment of relational structure that paved the way for a more difficult match involving the same relational pattern. We note that there might have been a progressive alignment effect in Experiments 1 and 2 as well, in that children might have benefitted from the first easier identical-items task when performing the more difficult cross-mapping task. However, consistent with the second prediction above, the relative difficulty of the cross-mapping task was greater for iconic symbols (as in Experiments 1 and 2) than for abstract symbols (as in Experiments 3a and 3b).

Structure Mapping Between Maps and Spaces

Following from the central hypothesis that map reading is accomplished via analogical processing, our second prediction was that guiding children through the process of structure mapping between maps and spaces can help them to better understand maps. We tested this prediction by asking whether guided-alignment training—designed to reveal one-to-one correspondences and parallel relational structure—would improve children's map understanding, especially for more difficult maps. In Experiment 1, children who received guided alignment were more successful than a control group. Whereas Experiment 1 had used a combination of gesture and language in the guided-alignment condition, in Experiment 2, we contrasted a gesture condition with a language condition. We found no difference between these two conditions in the identical-items task; however, there was an advantage of gesture over language in the difficult cross-mapping task (possibly because of the effectiveness of the back-and-forth gesture used to indicate the correspondences). In Experiment 3a, we applied the guided-alignment technique (using gestures, as in Experiment 2) to maps with abstract symbols (dots indicating spatial locations). We found the predicted advantage of the guided-alignment condition over the control condition in the identical-items task. Interestingly, children from both groups performed surprisingly well on the cross-mapping task. Two factors may have contributed to this result: (a) Color mismatching in Experiment 3a may be a less distracting factor to children than whole object mismatching in Experiments 1 and 2, and (b) children may have benefited from the earlier easier task, as predicted by the principle of progressive alignment.

Overall, we found that guided-alignment training improved children's map reading performance. We suggest that the benefit of guided alignment stems from two essential components of analogical mapping—one-to-one correspondence and parallel relational structure (Gattis, 2002, 2004; Gentner, 1983; Gentner & Markman, 1997; Liben, 2009; Loewenstein & Gentner, 2001; Uttal, Gentner, Liu, & Lewis, 2008; Uttal & Yuan, 2014). One-to-one correspondence helps children to understand that a symbol on a map corresponds to a specific location in the space. Although more exploration is needed, our results suggest that the correspondences between maps and spaces were conveyed more effectively (at least

to 3-year-olds) with back-and-forth correspondence gestures than by using identical linguistic labels for symbols and referents. These findings are consistent with Richland and McDonough's (2010) suggestion that gestures can provide strong visual cues to draw learners' attention to the correspondences between two representations. More broadly, our results are consistent with the idea that gestures can spatialize important conceptual information (Alibali, 2005; Goldin-Meadow, 1999), including analogical structures (Cooperrider, Gentner, & Goldin-Meadow, 2016).

The second support of analogical reasoning is parallel relational structure, which can help children to understand that the spatial relations among objects in the space correspond to the spatial relations among icons on a map. It appears that both relational gesture (the arcing movement that emphasized parallel spatial relations) and relational language (the spatial term "between" and the numerical terms "first, second, third") supported children's understanding of parallel relational structure. However, the effect of relational language on children's understanding of spatial representations was not as strong as anticipated (Miller et al., 2015). Prior studies have shown that relational language can help children understand the spatial structure of a domain and thereby improve their ability to carry out mapping tasks (Casasola, 2005; Gentner & Christie, 2006; Gentner et al., 2013; Loewenstein & Gentner, 2005). It is possible that a different set of linguistic terms would be more effective in promoting relational thinking in this task (Plumert & Nichols-Whitehead, 2007). Future studies should investigate the effects of different kinds of relational language (e.g., spatial, ordinal, feature) on children's relational thinking.

Although we argue that the patterns observed here are best explained by an analogical mapping account, we acknowledge that multiple factors may be at play in the current studies. For example, one interesting alternative perspective would be an activation model framework, which would provide a more fine-grained way of accounting for performance (Diamond, 2013; Marcovitch & Zelazo, 2009; Munakata et al., 2011; Zelazo et al., 2003). One way to think about children's performance across experiments is that the strength of the object match is influenced by similarities in shape, color, and position between the symbols in the map and those in the space. In Experiments 1 and 2, both shape and color matched, resulting in high performance on the identical-items task and poor performance on the cross-mapping task (in which object correspondence was the misleading strategy). In contrast, when objects on the map and those in the room had the same color but different shape (Experiment 3), object matching was less strongly activated, resulting in a stronger spatial correspondence and better performance on the cross-mapping task. Our account is compatible with this perspective, which seems to provide a plausible explanation for children's performance from the baseline conditions. However, a unique contribution of the current study is the demonstration that guided alignment based on analogical reasoning led to better performance for children in the training conditions.

An important direction for future work is to specify how gesture and language lead young children to shift focus from object matching to relational mapping. Prior studies have suggested that this change can be driven both by gains in relational knowledge (Gentner, 2003, 2010; Gentner et al., 2011; Rattermann & Gentner, 1998), and by increases in working memory and executive control capacity (Halford, 1992; Morrison, Doumas, & Richland, 2011; Richland & Burchinal, 2013; Thibaut, French, & Vezneva, 2010). Although the current work did not set out to test these accounts, multiple factors may be at work in the development of the relational shift. Future work in this regard would be helpful in specifying the mechanisms of change in relational thinking.

Implications for Development

Consistent with several prior studies (Chen, 1996; Gattis, 2002; Loewenstein & Gentner, 2001, 2005; Uttal et al., 2001, 2008), our research suggests that structure-mapping processes are a crucial learning mechanism through which children develop understanding of spatial representations (Gentner, 2010). Prior research has shown that children initially judged photographs to be similar to their referents on the basis of surface object similarity, and only gradually began to appreciate their relational similarity (Uttal et al., 2008), consistent with the relational shift seen in analogical development (Gentner & Rattermann, 1991; Richland et al., 2006). We also draw on evidence that techniques that aid children's insight into the common relational structure between two spaces, such as encouraging children to compare two model rooms (Loewenstein & Gentner, 2001) or providing them with spatial relational language (Loewenstein & Gentner, 2005), can improve children's performance in spatial search tasks. Building on these prior studies, we extended the research on analogical mapping and learning of spatial representations to the domain of map reading. Our research highlights the important role analogy plays in children's understanding of spatial representations and relational thinking in general. We have shown that (a) children's map reading follows the same pattern as analogical reasoning in general, and (b) interventions that are designed to facilitate the process of analogical mapping can promote children's ability to extract relational patterns and carry out relational mappings.

Our findings also shed light on the role of iconicity in children's understanding of maps and other symbolic representations. *Iconicity* refers to the perceptual similarity between symbols and their referents (DeLoache, 1995; Frishberg, 1975; Wilcox, 2004). Many theories of cognitive development have emphasized that children benefit from iconic symbols that share a high degree of object similarity with their referents (Piaget, 1951; Werner & Kaplan, 1963). However, recent studies have shown that iconic representations can sometimes be detrimental to learning (Goldstone & Sakamoto, 2003; Kaminski & Sloutsky, 2013; Uttal, Liu, & DeLoache, 2006). Our research adds another perspective on the role of iconicity in symbolic understanding. We compared maps with iconic symbols (photographs of real objects) to maps with abstract symbols (dots). Children performed better with iconic symbols when object similarity between maps and spaces was consistent with the relational alignment (identical-items task); however, this same iconicity made it difficult for children to establish relational correspondence when object similarity competed with the correct structural alignment (cross-mapping task). Children were more likely to make object-matching errors when the cross-mapped objects were iconic (Experiment 1) than when they were abstract (Experiment 3a). Viewed within the theoretical context of analogy and comparison, iconic symbols that are consistent with the relational alignment can help children to establish a successful mapping, but iconic matches that are inconsistent with the relational alignment will make it *more* difficult for them to establish relational correspondences. Because relational correspondences are essential in maps and many other spatial representations, the potential drawbacks

and benefits of highly iconic symbols need to be considered in research and education.

Although understanding the analogical mapping between maps and spaces is an important foundation, map reading ability undergoes considerable changes throughout development (Presson, 1982). One crucial capacity is being able to establish alignment between maps and spaces. Previous research suggests that young children often do not rotate maps when they were misaligned with their referent space, resulting in many egocentric errors (Bluestein & Acredolo, 1979). It is not until Age 5 or 6 that children spontaneously rotate misaligned maps (Presson, 1982). The issue of alignment is not only important for viewing maps statically, but perhaps even more so, when one uses maps for navigation; moving in the environment requires the constant update of one's position in relation to other landmarks, completing necessary rotation to align the map with the world, as well as planning routes according to the information on the map (Sandberg & Huttenlocher, 2001). Research shows a marked developmental difference in children's ability to use maps in navigation with children as young as Age 3 can use simple maps to follow easy routes but also considerable development over time (Blades & Spencer, 1986; Sandberg & Huttenlocher, 2001).

Another important capacity that is crucial to connecting maps to their referent spaces is the understanding of scaling (Huttenlocher, Vasilyeva, Newcombe, & Duffy, 2008; Jirout & Newcombe, 2014; Liben & Downs, 1989; Presson, 1982). Frick and Newcombe (2012) demonstrated that children's performance at a scaling task decreases with an increase in scaling disparity (e.g., map to space ratio from 1:2 to 1:4). There is also a marked age effect, with adults and older children (5- and 6-year-olds) performing better than young children (3- and 4-year-olds). The difficulty as well as the malleability of scaling skills can also been seen from studies on other related forms of spatial representations. For example, many college students have difficulty understanding the magnitude of time between large-time-scale geological events (Libarkin, Kurdziel, & Anderson, 2007). Resnick, Shipley, Newcombe, Massey, and Wills (2012) found that prompting structural alignment across representations of geological time at different time scales helped students perform better at connecting small-scale representations to the very large time scale of geological events. Resnick et al.'s (2012) findings dovetail with our findings in suggesting that techniques based on comparison and alignment may benefit adults as well as children, especially for challenging tasks that involve large scaling disparities. Thus, the extant research on reading maps, in particular, and other spatial representations, in general, entails a protracted development with marked age difference and individual difference that can be improved with training and a better understanding of the processes involved in the tasks (Uttal et al., 2012).

Conclusions

Our findings add to a growing body of literature (Gattis, 2002; Gattis & Holyoak, 1996; Loewenstein & Gentner, 2001, 2005; Resnick et al., 2012; Uttal et al., 2008) suggesting that the mechanisms of analogical mapping may underlie the learning and use of spatial representations. Children's map reading follows the same learning trajectory as their understanding of analogical processing—children learn to establish correspondences between maps and spaces based on object similarity before they can do so based on relational similarity. Interventions designed to foster the establishment of one-to-one correspondence and parallel relational structures are effective in helping children understand and use maps. Furthermore, these results help to clarity how iconicity contributes to children's understanding of symbolic representations. Theories of analogical reasoning therefore offer a general framework through which we can better understand the developmental mechanism underlying children's emerging ability to understand and make use of spatial representations.

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Appendix

Detailed Description of the Scripts and Experimental Procedures

Order	Procedure
	E1: Guided alignment condition
1	"There are three chairs in the room, the **first** chair, the **second** chair, and the **third** chair" [pointing to each chair in sequence from left to right].
2	"There are three chairs on the map too, the **first** map chair, the **second** map chair, and the **third** map chair" [pointing to each chair in sequence from left to right].
3	"The first map chair [pointing to the left chair on the map] goes with the first chair [pointing to the left chair in the room]." Repeat the same procedure for the middle and right chair.
4	"The second map chair is in **between** the first map chair and the third map chair on the map" [pointing to each chair while referring to it].
5	"The second chair is in **between** the first chair and the third chair in the room too" [pointing to each chair while referring to it].
6	"Do you see, this chair [pointing to the middle chair on the map] and this chair [pointing to the middle chair in the room] are in the very same place?" [**pointing back-and-forth** between them]
	E2 & E3a: Gesture condition
1	"There are three chairs in the room, here, here, and here" [pointing to each chair in sequence from left to right].
2	"There are three chairs on the map too, here, here, and here" [pointing to each chair in sequence from left to right].
3	"This chair [pointing to the left chair on the map] goes with this chair [pointing to the left chair in the room]." Repeat the same procedure for the middle and right chair.
4	"Look, this goes here, and goes here" [pointing to each object on the map in a left-right sequence with an **arcing movemen**t between each contiguous pair of objects].
5	"Look, this goes here, and goes here" [pointing to each object in the room in a left-right sequence with an **arcing movemen**t between each contiguous pair of objects].
6	"Do you see, this chair [pointing to the middle chair on the map] and this chair [pointing to the middle chair in the room] are in the very same place?" [**pointing back-and-forth** between them].
	E2: Language condition
1	"There are three chairs in the room, the **first** chair, the **second** chair, and the **third** chair" [pointing to each chair in sequence from left to right].
2	"There are three chairs on the map too, the **first** map chair, the **second** map chair, and the **third** map chair" [pointing to each chair in sequence from left to right].
3	"The second map chair is in **between** the first map chair and the third map chair on the map" [pointing to each chair while referring to it].
4	"The second chair is in **between** the first chair and the third chair in the room too" [pointing to each chair while referring to it].
5	"Do you see, this chair [pointing to the middle chair on the map] and this chair [pointing to the middle chair in the room] are in the very same place?"

Note. Bolded are the essential techniques used to convey one-to-one correspondence and parallel relational structure.

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