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Young Children's Representations of Spatial and Functional Relations Between Objects

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Three experiments investigated changes from 15 to 30 months of age in children's (N = 114) mastery of relations between an object and an aperture, supporting surface, or form. When choosing between objects to insert into an aperture, older children selected objects of an appropriate size and shape, but younger children showed little selectivity. Further experiments probed the sources of younger children's difficulty by comparing children's performance placing a target object in a hole, on a 2-dimensional form, or atop another solid object. Together, the findings suggest that some factors limiting adults' object representations, including the difficulty of comparing the shapes of positive and negative spaces and of representing shapes in 3 dimensions, contribute to young children's errors in manipulating objects.

During the 2nd and 3rd years of life, children begin to attempt to pile blocks on top of one another, put lids on pans, and insert objects into holes. The ability to solve such problems provides a window into children's developing spatial perception, mechanical reasoning, and goal-directed action. Nevertheless, the changing capacities that propel this development, and the cognitive problems that children must overcome, are poorly understood. The present research aims to contribute to this understanding through studies of children's developing abilities to manipulate objects in relation to one another.

The difficulties young children face when they manipulate objects can be striking and puzzling to adults. Consider the task of fitting an object into a hole: To an adult, it is obvious that a square peg fits into a square, and not a round, hole; children, however, may struggle for months before achieving this insight. Young children's repeated failures on this apparently easy task have long suggested a mismatch between the object representations of children and adults.

On closer examination, however, the task of fitting objects into holes calls on processes that cause difficulties for adults as well as children. To fit an object into an aperture, actors must solve five problems. First, they must represent the spatial relations between a solid object's three-dimensional shape and the shape of its two-dimensional silhouette. This problem is made more difficult by the fact that for most objects, even those with simple and symmetrical shapes, many such silhouettes exist. For example, a regular cylinder has a circular silhouette from a viewpoint parallel to its spine, a rectangular silhouette from a viewpoint perpendicular to its major axis, and a family of silhouettes of more complex shapes from other viewpoints. Even when the shapes of objects are highly familiar, we may have difficulty representing their silhouettes (e.g., determining the shape of the silhouette of a cube that is perched on one vertex: see Pani, Jeffres, Shippey, & Schwartz, 1996). Moreover, adults often fail to recognize objects from unfamiliar viewpoints (Rock, 1974; Tarr, 1995) and overcome this limit by

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developing knowledge of the appearance of objects from diverse views (Tarr & Bülthoff, 1995, 1998). For children, even simple objects are relatively novel, and so children may find it especially hard to compute their relevant silhouettes.

The second problem posed by the blocks-and-holes task stems from the need to relate the shape of a positive space (the block) to that of a negative space (the hole). Although adults can describe the shapes of both positive and negative spaces (Palmer, 1999; Peterson, 2003), negative spaces often are not seen as having definite shapes and instead appear to extend indefinitely behind the borders of the surfaces that enclose them (Baylis & Driver, 1995; Driver & Baylis, 1995; Rubin, 1921). Because shapes are typically parsed into parts at points of maximum concavity, moreover (Feldman & Singh, 2005; Hoffman & Richards, 1984), a hole that does receive a shape description often will be represented differently from its complementary object (Bertamini & Croucher, 2003). In the celebrated face–vase illusion, for example, adults do not perceive the vase as having the outline shape of a face, even though it is bounded by a contour in the shape of a face profile, because the face and vase are given different part descriptions. The shape description of an object therefore tends to differ from that of a hole with the same outline contour.

The third representational problem in the blocks-and-holes task concerns the need to rotate an object mentally to determine its properties at a new orientation. In shape-fitting tasks, an object will fit through a hole only at special orientations. Unless the object is spherical, the critical orientation will differ from the orientation at which the object is initially encountered, and so the child must rotate the object mentally if she is to determine in advance whether the object can be made to fit through the hole. Mental rotation is a time-consuming and sometimes difficult task for adults (Cooper & Shepard, 1984). When the forms of two objects are complex, such as crumpled paper, the task becomes nearly impossible for adults (Rock, 1974). Since even simple three-dimensional shapes are less familiar to young children than to adults, young children may find it difficult to imagine novel orientations of simple shapes for the same reasons that adults find it difficult to imagine novel orientations of complex shapes (see Levine, Huttenlocher, Taylor, & Langrock, 1999).

Studies of visual cognition in adults suggest, therefore, that fitting objects into holes could be difficult for children for three reasons if children's representations of objects depend on mechanisms and processes that are shared by adults. The hole-fitting task could be difficult for two further reasons, however, because of the demands it places on children's memory and capacity for goal-directed action. When an object is pushed through a hole into an opaque container, it moves quickly out of view. Discovering the spatial properties of the object that allowed its passage therefore requires that children summon up and analyze a representation of a now-absent object. When faced with a choice between two objects or two apertures, moreover, children must first choose the appropriate three-dimensional orientation of an object relative to an aperture, and then they must grasp the correct object in a manner that allows it to be rotated into the correct orientation prior to insertion. This task requires that children represent the present state in relation to the goal state, and choose the sequence of actions that will bring about the goal state.

Object-fitting tasks therefore provide a window on the early development of spatial cognition, memory, action, and problem solving. Perhaps for this reason these tasks figure prominently in intelligence tests for young children (Bayley, 1969; Kelly-Vance, Needelman, Troia, & Oliver Ryalls, 1999). The Bayley Scales of Infant Development–Second Edition (BSID–II) confirm research findings that 1-year-old children can insert an object into a hole (Bayley, 1969; Gesell & Thompson, 1934; Hayashi, 2007; Hayashi & Matsuzawa, 2003), especially if the orientations of the object and hole are aligned (McKenzie, Slater, Tremellen, & McAlpin, 1993). When objects have complex shapes, however, fitting tasks have long been known to cause difficulties for children as old as 3 years (Meyer, 1940).

In an initial experiment, Örnkloo and von Hofsten (2007) provided evidence for a regular development of these abilities. The experiment presented 14- to 26-month-old children with a box with a hole in its top that varied in shape, and with a single three-dimensional oblong object that fit snugly through the hole at an orientation perpendicular to that of its initial presentation. The experiment investigated children's capacity for planning a fitting action by measuring how children handled the object, which needed to be rotated before insertion. Children of all ages showed great interest in the task and motivation to perform it. At all ages, they reached for the object readily and brought it down on top of the hole with the evident intention to push it through. Nevertheless, 14- and 18-month-old children approached the problem quite differently from the older children. At 14 months, children virtually ignored the object's orientation in their attempts to put it through the hole. At 18 months, children appeared to realize, intermittently, that the task required rotation of the object, but they rarely rotated the object correctly or succeeded at the task. In contrast, the 22- and the 26-month-old children performed quite well: They lifted the object and turned it to the appropriate orientation prior to making contact with the box.

Although Örnkloo and von Hofsten's (2007) experiment confirmed a developmental change in children's performance of this task, the underlying nature of this change is not clear. It is possible that younger children were stymied by one of the three representational tasks described earlier: detecting the relation between a three-dimensional object and its two-dimensional silhouette, detecting the relation between a positive and a negative space, or performing mental alignment of one shape to another. Alternatively, children of all ages may have solved these tasks, but the younger children may have been hampered by the memory demands of representing the spatial properties of objects that have moved out of view or by the need to harness these perceptual and cognitive abilities in the service of goal-directed action. Just as young children may perceive the existence and location of a hidden object but fail to search effectively for the object (Hood, Cole-Davies, & Dias, 2003; Mash, Novak, Berthier, & Keen, 2006), children may perceive the spatial relation between an object and an aperture and yet fail to exploit that relation effectively so as to push the object through the aperture.

Further experiments by Örnkloo and von Hofsten (in press) help to distinguish these possibilities. In these experiments, children aged 20, 30, and 40 months were introduced to the block-fitting problem as described previously and then were presented with two different choice tasks. In one task, they were shown a single aperture and two objects of different shapes, such that one of the objects could be rotated to fit through the hole but the other could not. In the other task, children were shown a single object and two apertures of different shapes such that the object could be rotated to fit through one of the two holes but not the other. Children's choices of objects and holes were recorded. If young children perceive the appropriate spatial relations between the objects and apertures but fail to act in an appropriate goal-directed manner, then children should choose the correct object or aperture initially, even if they fail to rotate the object correctly so as to push it through the aperture.

Three findings emerged from this experiment. First, the object- and aperture-choice tasks were *more difficult* than the fitting task presented in the first experiment. Whereas 22- and 26-month-old children had succeeded at the task of fitting a single object into a single aperture, even 30-month-old children made errors on the choice tasks, and 20-month-old children performed completely at chance. Second, older children's performance varied with the symmetry of the object. When children were presented with simple shapes with multiple symmetries (e.g., circles, squares) they tended to choose the correct aperture or object. When they were presented with objects with fewer symmetries (e.g., rectangles, right triangles), they tended to fail the task. Third, older children performed better in the aperture-choice task than in the object-choice task. Because the motor demands of selecting between two objects or apertures were minimal, these findings suggest that the difficulty of object- and aperture-fitting tasks stems in part from cognitive problems the task presents.

But what are the cognitive problems that impair young children's performance? Are young children, like adults, hindered by limited abilities to relate an object's three-dimensional shape to its two-dimensional silhouette, to relate the positive shape of an object to the negative shape of an aperture, or to rotate a three-dimensional object in their minds? The present experiments attempt to test for these sources of difficulty, both by varying the properties of the objects and apertures that are relevant to the hole-fitting task and by varying the task itself.

In these experiments, we compare the difficulty of object- and aperture-choice tasks when the relevant variable that distinguishes the two objects or apertures is either *shape* or *size.* Size and shape are interesting variables to consider in choice tasks because they are relevant to object–aperture relations in different ways. Although objects can only fit through apertures that are larger than the object itself, the relevant size relations can be determined in many cases (and in all the cases tested here) without any mental rotation of the object, and without any analysis of its shape, provided that the aperture is larger in all directions than the object's largest silhouette. If the challenges of mental rotation or of comparing the shapes of positive and negative spaces limit young children's performance on object-fitting tasks, children should perform better on hole-insertion tasks when the relevant variable is size rather than shape.

In Experiments 2 and 3, moreover, we assess and compare children's performance on three tasks that are similar to the hole-fitting task and that also draw on spatial representations of objects: a tower-building task in which children must place one object on top of another object of the same three-dimensional shape and size, a form-covering task in which children must place an object on top of a two-dimensional form with the same shape and size as one of the object's surfaces, and a puzzle task in which children insert an object into a shallow hole such that the shape and size of the object remain visible. Because the different experimental tasks make differing demands on memory and spatial representation, a comparison of children's performance should help to shed light on some of the sources of children's difficulty at fitting blocks into holes.

Experiment 1

Children aged 15, 20, and 30 months first were introduced to an object-fitting task and then were presented with a single aperture and two objects, one of which fit snugly through the aperture, and their choice between the objects was measured. When the correct object was positioned appropriately with respect to the aperture, it fell quickly and disappeared completely from view. Children's attempts to analyze the sources of successful trials therefore required that the relevant properties of the object be retrieved from memory.

On all trials, one of the objects had a size and shape that matched the aperture and the other object was inappropriate either in size, in shape, or on both dimensions. The objects were a cube, whose shape creates different two-dimensional silhouettes at different orientations, and a sphere, whose silhouette is invariant over changes in orientation.

Method

Participants. The participants were 48 healthy children living in the region of Uppsala, Sweden. The youngest group consisted of sixteen 15-month-old children (8 girls; mean age = 15.1 months, *SD* = 7.0 days), the middle group consisted of sixteen 20-month-old children (8 girls; mean age = 19.5 months, *SD* = 18.8 days), and the oldest group consisted of sixteen 30-month-old children (8 girls; mean age = 29.4 months, *SD* = 30.7 days). The families of the participants were primarily White middle class, with parents having at least a high school education.

Materials. The stimuli were balls and cubes of two sizes and a variety of colors, and a box with a circular or square hole in one of two sizes. The objects and the box were presented on a table (59.5 × 120 cm) between the experimenter and the child. The upper surface of the box had a square shape (14 × 14 cm), a height of 11.5 cm, and was fixed to the table 5 cm from the edge on the side where the subject was seated. The objects were presented on a platform positioned behind and at the same level as the lid of the box. Different lids could be applied to the box. Each lid had a central aperture of one of two sizes and shapes: circular (3.5 or 6.0 cm in diameter) or square (3.6 or 6.0 cm side). The objects to be fitted were balls and cubes that came in two different sizes with cross-sections 1 mm smaller than the apertures so that they fit snugly into the appropriate aperture. There were four differently colored copies of each object (red, blue, yellow, and green; see Figure 1). One video camera was placed above the table to record the testing session.

Procedure. After greeting the child and parent, the experimenter explained the purpose of the study, obtained parental consent, and played with the child to put him or her at ease. The parent was then invited to sit in an adjustable chair with the child in his or her lap, so that the child could see the cross-sections of the objects without any problems. The parent was permitted to encourage the child but not to give any assistance in the trials. The experimenter sat opposite to the child and presented the displays.

First, the child was introduced to the box with one lid and aperture in place. For training, the experimenter placed a small steel rod through the aperture and then handed a second rod to the child so that he or she could manipulate it and insert it into the box. The experiment did not start until the child had put at least one object into the hole. On

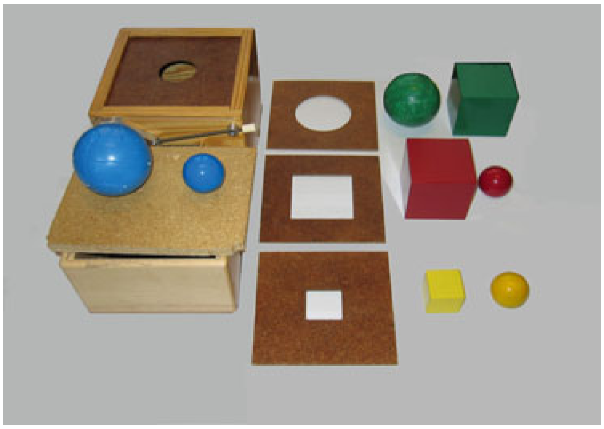

Figure 1. Materials for the hole-fitting task of Experiment 1.

each test trial, the experimenter positioned a new lid on the box, pointing at the aperture in the lid so that the child was aware of its shape and size. Then, the experimenter held up two objects, one correct, one incorrect, in front of the child with the appropriate cross-section clearly visible and said, ''Which object fits the hole?'' After that, the two objects were placed side by side on the platform in front of the child at the far side of the box. The child was encouraged to pick up one of the two objects and insert it through the fitting aperture of the box. If the child had picked the correct object but could not insert it, the experimenter assisted with the insertion to avoid the child's eventual frustration. After the trial, both objects were moved out of reach and view. The duration of the whole experiment was variable, but most of the children finished the session within 20 min.

Design. The experiment consisted of 24 trials, 6 with each aperture. Each aperture was combined with the correctly fitting object paired with one of the other three objects (different size, different shape, or different size and shape) on two trials, with the positions of the two objects reversed between these trials. The aperture and the pair of objects were changed between each trial. Colors of objects were constant within a trial and varied across trials to maintain interest. The trials were presented in a different randomized order for each subject.

Data coding and analysis. A trial was considered completed when the child picked up an object, transported to the aperture, and tried to insert it. If the child picked up one of the objects, moved it toward the aperture with the presumed intention to insert it, but then changed his or her mind before touching the lid and picked up the other object, only the second object was counted. This happened on 4.4% of the trials. Eight children from each age group were coded by a second coder. The two coders agreed on 100% of trials.

On shape difference trials, size difference trials with a small aperture, and shape + size difference trials with a small aperture, only one of the objects presented to the child could fit through the aperture. On size difference trials with a large aperture and shape + size difference trials with a large aperture, both objects presented to the child could fit through the aperture. Nevertheless, to maintain consistency and a balanced design, children's responses on all trials were coded as correct match if they chose the (one) object that matched the aperture exactly, and performance was compared to chance (50%).

Results

The task of inserting objects into the box proved to be very attractive. Out of 24 possible trials per age, 15-month-old children completed an average of 23.4 trials and the two older age groups completed an average of 22.8 trials. No child was excluded due to fussing or fatigue. Preliminary analyses revealed no effect of gender, so this variable was not considered further.

A repeated measures analysis of variance (ANOVA) with age (15, 20, and 30 months) as a between-subject factor and trial type (size, shape, and size + shape) as a within-subject factor revealed a main effect of age, $F(2, 45) = 32.69$, $p < .001$, $\eta_p^2 = .59$, but no main effect of trial type, $F(2, 90) = 1.62$, *ns*, $\eta_p^2 = .04$, and no interaction of Age × Trial Type, $F(4, 90) = 1.07$, *ns*, $\eta_p^2 = .05$. Tukey's honestly significant difference (HSD) post hoc tests indicated that the performance of 30-month-old children exceeded the performance of both 15- and 20-month-old children (*p*s < .001) but that the two youngest groups did not differ from one another. Further analyses were conducted to examine performance on size, shape, and size + shape trials separately since different object properties were relevant in each case.

Size trials. A repeated measures ANOVA with age (15, 20, and 30 months) and aperture size (small and large) as within-subject factors revealed a significant effect of age, $F(2, 45) = 16.57$, $p < .001$, $\eta_p^2 = .42$; a significant effect of aperture type, $F(1, 45) = 54.56$, $p < .001$, $\eta_p^2 = .55$; and a significant interaction of age and aperture type, $F(2, 45) = 7.15$, $p < .01$, $\eta_p^2 = .24$. Children were more likely to choose the object that matched the aperture on small aperture compared to large aperture trials, and this difference was most pronounced for the 20-month-old children. Table 1 and Figure 2a present the performance means and results of one-sample *t* tests for small and large aperture trials at each of the ages.

Shape trials. An ANOVA with age (15, 20, and 30 months) as a between-subject variable and aperture shape (circle and square) as a within-subject variable indicated main effects of age, $F(2, 45) = 18.28$, $p < .001$, $\eta_p^2 = .45$, and aperture shape, $F(1, 45) = 40.03$, $p < .001$, $\eta_p^2 = .47$, but no interaction of Age × Aperture Shape, $F(2, 45) = 1.32$, *ns*, $\eta_p^2 = .06$. Overall, children showed a tendency to choose the ball over the cube, performing above chance on trials with a circular aperture, $M = 79\%$, $SD = 21$, $t(47) = 9.62$, $p < .001$, $d = 1.39$, and below chance on trials with a square aperture, $M = 37\%$, $SD = 34$, $t(47) = 2.67$, $p < .05$, $d = 0.38$. Table 1 and

Table 1
Percentage of Matching Responses for All Trial Kinds in Experiment 1

Trial type	Aperture	Matching object	Nonmatching object	% matching 15 months	% matching 20 months	% matching 30 months
Shape	○	●	▪	81 (25)	78 (32)	75 (37)
Shape	◯	⬤	■	72 (36)	69 (40)	97 (13)
Shape	▫	▪	●	25 (37)	19 (31)	59 (42)
Shape	□	■	⬤	31 (40)	28 (36)	59 (42)
Size	○	●	⬤	59 (38)	78 (31)	97 (13)
Size	▫	▪	■	59 (33)	84 (30)	91 (20)
Size	◯	⬤	●	41 (38)	22 (36)	59 (33)
Size	□	■	▪	44 (36)	19 (25)	69 (36)
Shape + size	○	●	■	28 (31)	91 (20)	91 (20)
Shape + size	▫	▪	⬤	63 (43)	59 (38)	81 (31)
Shape + size	◯	⬤	▪	50 (40)	28 (31)	72 (36)
Shape + size	□	■	●	25 (41)	13 (29)	59 (38)

Note. Numbers in parentheses indicate the standard deviation of the mean.

Figure 2b present performance means and results of one-sample t tests for both aperture types at each of the ages.

Size + shape trials. An ANOVA with age (15, 20, and 30 months) as a between-subject factor, and aperture size (small and large) and aperture shape (circle and square) as within-subject factors revealed main effects of age, $F(2, 45) = 14.74$, $p < .001$, $\eta_p^2 = .40$; aperture size, $F(1, 45) = 31.23$, $p < .001$, $\eta_p^2 = .41$; and aperture shape, $F(1, 45)= 4.49$, $p < .05$, $\eta_p^2 = .09$, on performance. There was a significant interaction of Age × Aperture Size, $F(2, 45) = 8.05$, $p < .01$, $\eta_p^2 = .26$, as well as marginal interactions of Age × Aperture Shape, $F(2, 45) = 3.04$, $p = .058$, $\eta_p^2 = .12$, and Aperture Shape × Aperture Size, $F(1, 45) = 3.07$, $p = .087$, $\eta_p^2 = .06$. Finally, there was a significant three-way interaction of Age × Aperture Size × Aperture Shape, $F(2, 45) = 6.38$, $p < .01$, $\eta_p^2 = .22$. Twenty- and 30-month-old children tended to perform best on small circle aperture trials, followed by small square, large circle, and large square aperture trials, but 15-month-old children performed best on small square aperture trials, followed by large circle, large square, and small circle aperture trials. Table 1 and Figure 2c present means and results of one-sample t tests for all aperture types at each of the ages.

Discussion

Fifteen-month-old children performed at or below chance for all trial types except for circular aperture shape trials, whereas 30-month-old performed well on all trial types except for square aperture shape trials and large aperture shape + size trials. Performance by 20-month-old children was mixed, with success on a handful of trial types but chance or below-chance performance on other trial types.

Two features of the findings complicate the interpretation of these patterns of performance. First, on size trials, both 20- and 30-month-old children tended to choose the small object over the large object and therefore appeared to perform well on small aperture size trials and poorly on large aperture trials. This pattern of performance could have two explanations. First, children may have understood the size relations between the object and the aperture, and realized that the smaller object would fit more easily than the larger object into apertures

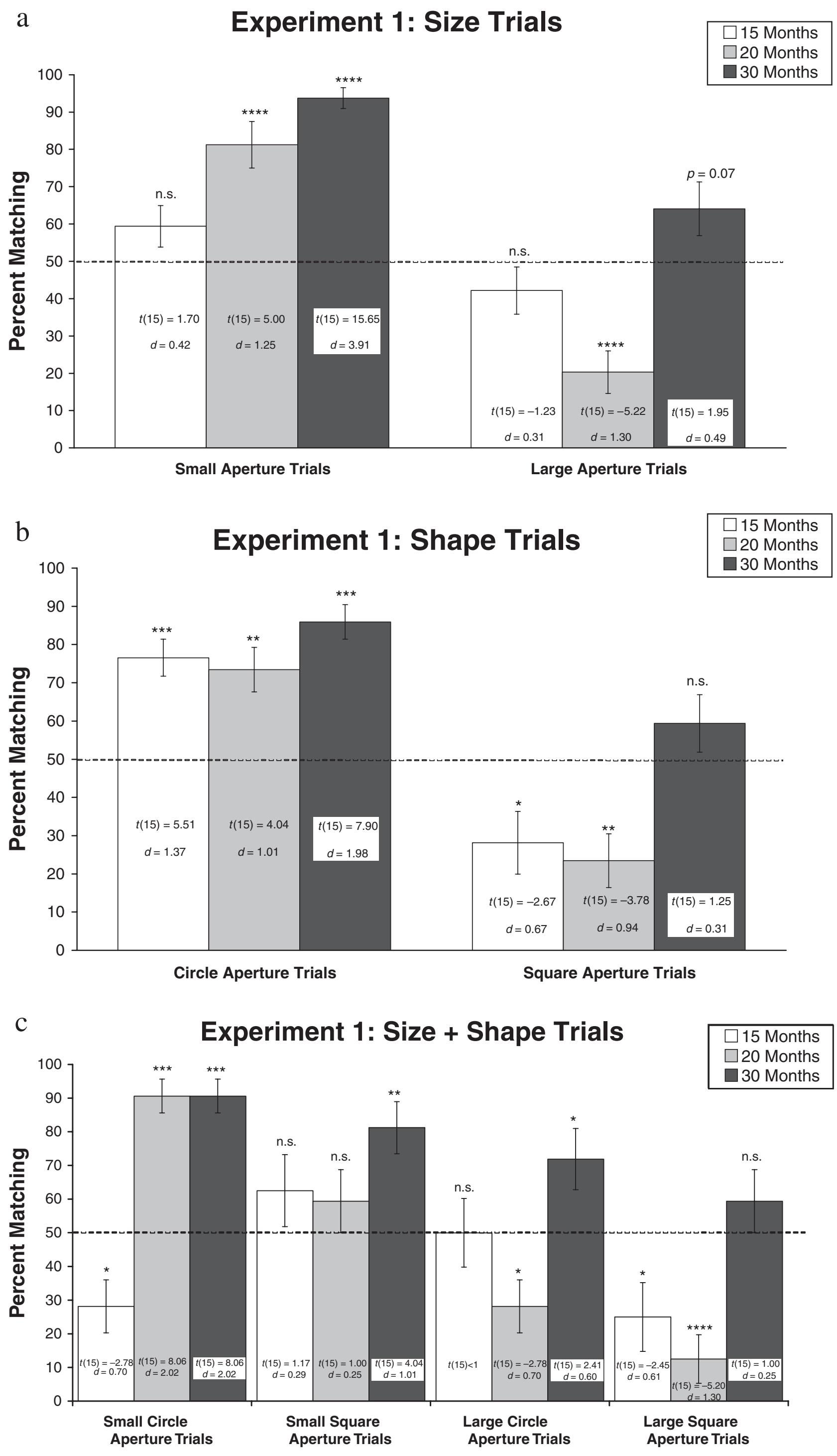

Figure 2. Performance on (a) size, (b) shape, and (c) shape + size trials in Experiment 1.
Note. Error bars represent the standard error. Asterisks indicate bars that are significantly different from chance.
*p < .05. **p < .01. ***p < .001.

of *both* sizes, and thus reasonably regarded the smaller object as always correct. Alternatively, children may have chosen the smaller object simply because it was more attractive or easier to grasp. The present data cannot distinguish between these interpretations.

Second, collapsing across aperture type (circle and square), 15- and 20-month-old children performed at chance on shape trials $M = 52\%$, $t(15) < 1$, and $M = 48\%$, $t(15) = -1.00$, whereas 30-month-old children performed above chance, $M = 73\%$, $t(15) = 5.46$, $p < .001$. Nevertheless, children of all ages performed above chance on shape trials with a circular aperture and showed a marked baseline preference for the ball over the cube on trials involving shape comparisons (Figure 2b). It is possible that children of all ages were capable of selecting the correct object on shape trials but that a tendency for younger children to choose the sphere under many (though not all) task conditions masked this understanding in the youngest children. Moreover, the reason for children's preference for the ball is not clear. Children may have preferred the sphere (irrespective of its relation to the aperture) because it is invariant over rotation: a property that is relevant to the demands of the fitting task. Alternatively, the sphere may have been preferred because it is easier to grasp or for other reasons unrelated to the spatial demands of the fitting task. The next experiments addressed some of these outstanding issues by presenting children with a choice between apertures rather than a choice between objects.

Experiments 2 and 3 were also undertaken, in part, to distinguish among some of the possible sources of young children's failure at the fitting task. Because younger children's poor performance in Experiment 1 may have stemmed from difficulties relating a positive space to a negative space or a three-dimensional shape to its two-dimensional silhouette, new tasks were devised that attempted to tease these problems apart. Because younger children may have been hampered by the rapid disappearance of the object through the hole, tasks were modified so that the object remained continuously visible. Thus, the next experiments investigated young children's performance with three fitting tasks that involved the same, continuously visible objects and that specifically contrasted in the demands placed on children's spatial representations of objects. Experiment 2 focused first on the performance of children at an intermediate age between those who succeeded and failed in the hole-fitting task of Experiment 1.

Experiment 2

Children aged 25–30 months were presented with three different tasks involving representations of the spatial relation of a three-dimensional object to its surroundings. On all three tasks, children placed an object on one of two bases that matched it either in size or in shape. One task, like that of Experiment 1, involved fitting a three-dimensional object into a hole. In contrast to Experiment 1, however, children were presented on every trial with a single tall object and two short boxes with different apertures (''hole task''; Figure 3a). When an object was placed in the box with the appropriate aperture, therefore, its top half remained visible.

The second task involved placing one three-dimensional object on top of another object of the same shape so as to form a tower (''tower task''; Figure 3b). In contrast to the hole-fitting task, the tower task required children to form and compare representations of one three-dimensional object to each of two three-dimensional bases. Moreover, all three arrays involved solid objects and so the task required no coordination between representations of positive and negative spaces.

The third task involved placing one three-dimensional object on top of a two-dimensional form of the shape of the object's silhouette (''form task''; Figure 3c). Like the tower task, this task required children to form a representation of the shape of one three-dimensional object and to compare its shape to that of two bases. In contrast to the tower task, however, the two bases presented two-dimensional shapes and therefore the task required no coordination between representations of multiple three-dimensional objects. Moreover, unlike the hole task, the form task did not require children to relate a positive space to a negative space. Because positive and negative spaces receive different shape (but not size) descriptions for adults, performance on the trials that required matching by shape might be easier for the form task than for the hole task.

To render the three tasks as comparable as possible, target object shapes were chosen so as to maximize the similarities between the two-object configurations that were created by placing the object in the hole, on the form, or on the other object (Figure 3). Moreover, the choice demands were equated: On each trial, the child chose between two bases on which to place a single object. Both to maximize the similarity of instructions across tasks and to encourage children to choose the correctly shaped base, the surfaces on which an object could be placed in each task were painted pink, and children were told to place the object on the base where it would cover this pink surface completely. This instruction was used in all three conditions, both to make the three tasks as

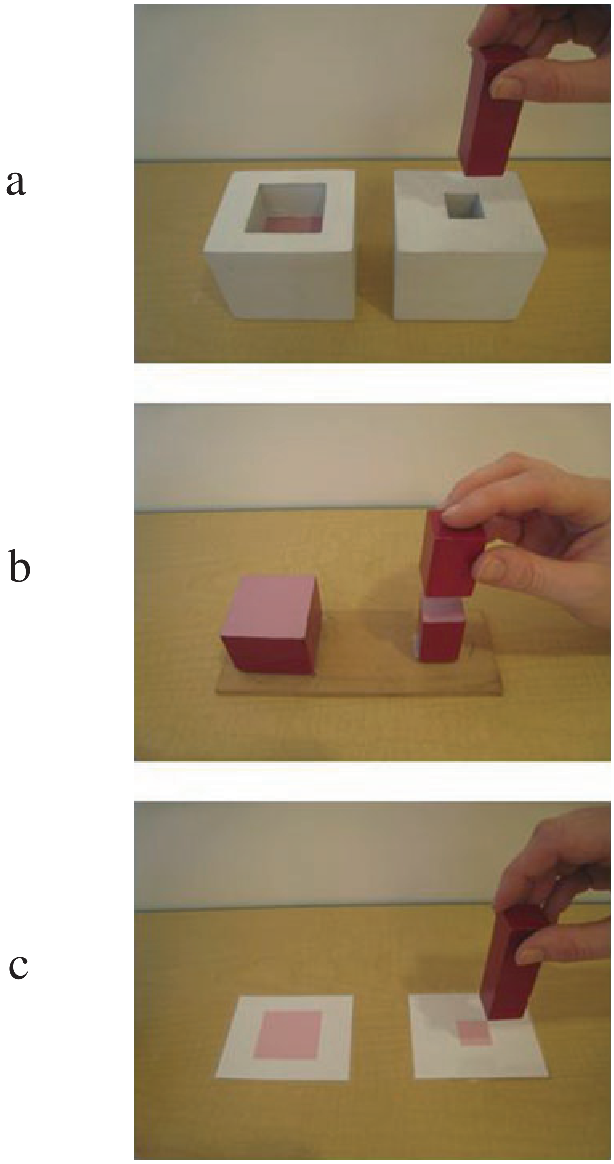

Figure 3. Example displays for size comparison trials in the (a) hole-fitting, (b) tower-building, and (c) form-fitting tasks of Experiment 2.

similar as possible and to encourage children to match objects to bases exactly. Although it was physically possible to place a small object onto or into a large base on all three tasks, doing so would leave part of the pink base visible, contrary to the task instructions.

Two further features of the experiment served to test whether children's difficulties with blocks and holes stem, in part, from limits to their representations of hidden objects or their capacities for mental rotation of object shapes. First, all three tasks of Experiment 2 involved objects whose shapes remained continuously visible throughout the task, eliminating the need for representations of the shapes of hidden objects. Second, all tasks were performed with a hole and an oblong with a circular cross-section on half the trials, and an oblong with a square cross-section on the rest. Because the circular-shaped oblong can be placed in correspondence with its hole without any mental rotation, but the square-shaped oblong must be rotated into correct correspondence, children might perform better on the trials with the circular shape if the demands of mental rotation limit their performance.

Method

Participants. The participants were 18 children from the greater Boston area. Children ranged in age from 25.1 to 30 months (8 females; mean age = 26.9 months, *SD* = 1.5 months). The families of the participants were primarily White middle or upper-middle class, with the majority of parents having at least a college education. Two additional children were tested but were excluded from analyses because they did not complete all the trials.

Materials. There were five different types of blocks whose cross-sections were in the shapes of a small equilateral triangle (3.25 cm sides: for training only), a small and large circle (2.75 and 5.5 cm diameter), and a small and large square (2.5 and 5 cm sides). All blocks were oblongs whose main axis was perpendicular to its distinctively shaped base, and they were either 7.5 cm tall (hole and form tasks) or 3.25 cm tall (tower task). In the hole task, the blocks could be fit into holes embedded in $10 \times 10 \times 10$ cm wooden bases. Each hole was approximately 3.75 cm deep, with an aperture slightly larger than the critical surface of the block that matched it (small triangle: 4 cm; small and large circles: 3 and 6 cm, respectively; small and large squares: 2.75 and 5.25 cm). In the tower task, the blocks could be placed on tower bases consisting of blocks of the same sizes and shapes as the target blocks. In the form task, the blocks could be placed on separate 10×10 cm pieces of laminated paper presenting solid forms of the same sizes and shapes as the critical surfaces of the target blocks at their centers. In all tasks, a training block was painted orange, whereas the test blocks were red, blue, yellow, and green. Moreover, the critical surfaces on which the child could place an object on the three types of bases were painted pink. These pink forms therefore were the same in the hole, tower, and form tasks.

Design. Each child was given four size trials followed by four shape trials in each of the three tasks (24 trials in total). Each size trial presented one of the four test blocks that varied in size (small vs. large) and shape (circular vs. square), paired with two bases of the same, congruent shape but different sizes. Each shape trial presented one of the same four test blocks paired with two bases of the same, congruent size but different shapes (circular or square). Lateral positions of correct bases were counterbalanced within and across participants at each age and in each task. The order of the three tasks was counterbalanced across participants in a full Latin square.

Procedure. Children were seated across the table from an experimenter. The hole task began with a training phase in which the experimenter demonstrated inserting the orange triangular block into a wooden base with the triangular hole, noting how she had ''covered the pink spot and made it fit.'' The experimenter then encouraged the child to do the same. On each of the test trials, the experimenter showed the child two wooden bases (tipping them forward to ensure the child had seen their two apertures with the pink bottoms) and then placed them side by side on the table and encouraged the child to ''cover the pink spot and make it fit.'' Following this, children were presented with the target block on the table between the child and the bases. When children made a correct response, the experimenter praised the child. When children made an incorrect response, the experimenter moved the block to the correct aperture and noted how she had ''covered the pink spot and made it fit.''

The tower task and the form task began with a training phase in which the experimenter demonstrated placing the orange triangular block onto the appropriate tower base or form, noting again how she had ''covered the pink spot and made it fit.'' After the child repeated this action, the experimenter proceeded to the test trials by showing the child the first pair of test tower or paper bases (tipping them forward to ensure the child had seen their pink-painted top surfaces) and then placed the bases or forms side by side on the table. The trials proceeded thereafter as in the hole condition, with the same instructions to ''cover the pink spot and make it fit.''

Data coding and analysis. A trial was considered correct if the child chose the endpoint that matched the block exactly. One coder scored the first endpoint chosen by each child on each trial and a second coder scored sessions of 4 children for reliability. The coders agreed on 100% of trials. Preliminary analyses revealed no effects of participant gender or task order; therefore, the data were collapsed over these variables in the analyses reported below.

Results

An ANOVA with task (hole, tower, and form) and trial type (size and shape) as within-subject factors revealed no effect of task, $F(2, 34) = 1.35$, *ns*, $\eta_p^2 = .07$; no effect of trial type ($F < 1$), and no interaction of Task × Trial Type ($F < 1$).

Size trials. An ANOVA with task (hole, tower, and form) and object size (small object and large object) as within-subject factors revealed only a significant effect of object size: Children were more likely to pick the endpoint that matched the object's size on large object trials than on small object trials, $F(1, 17) = 11.27$, $p < .01$, $\eta_p^2 = .40$. There was no effect of task ($F < 1$) and no interaction of task and object size ($F < 1$).

Children's performance on small and large object trials in the three tasks was compared to chance (50%) by one-sample t tests. On size trials in the hole task, children chose the base that matched the object on 64% of small object trials, $SD = 38$, $t(17) = 1.57$, $p = ns$, $d = 0.37$, and 89% of large object trials, $SD = 27$, $t(17) = 6.02$, $p < .001$, $d = 1.42$. In the tower task, children chose the matching base on 69% of small object trials, $SD = 34$, $t(17) = 2.31$, $p < .05$, $d = 0.54$, and 89% of large object trials, $SD = 21$, $t(17) = 7.71$, $p < .001$, $d = 1.82$. Finally, on size trials in the form task, children chose the matching base on 75% of small object trials, $SD = 31$, $t(17) = 3.43$, $p < .01$, $d = 0.81$, and 89% of large object trials, $SD = 21$, $t(17) = 7.72$, $p < .001$, $d = 1.82$ (see Figure 4a).

Shape trials. An ANOVA with task (hole, tower, and form) and object shape (circular and square) as within-subject factors revealed no effect of task, $F(2, 34) = 1.17$, *ns*, $\eta_p^2 = .07$; no effect of object shape ($F < 1$); and no interaction of Task × Object Shape ($F < 1$). Children performed above chance on shape trials in the hole task, $M = 75\%$, $SD = 27$, $t(17) = 3.91$, $p < .01$, $d = 0.92$, as well as on shape trials in the tower task, $M = 83\%$, $SD = 17$, $t(17) = 8.25$, $p < .001$, $d = 1.94$, and form task, $M = 83\%$, $SD = 28$, $t(17) = 4.97$, $p < .001$, $d = 1.17$ (see Figure 4b).

Discussion

The findings from the hole task of Experiment 2 confirm and extend one of the principal findings of

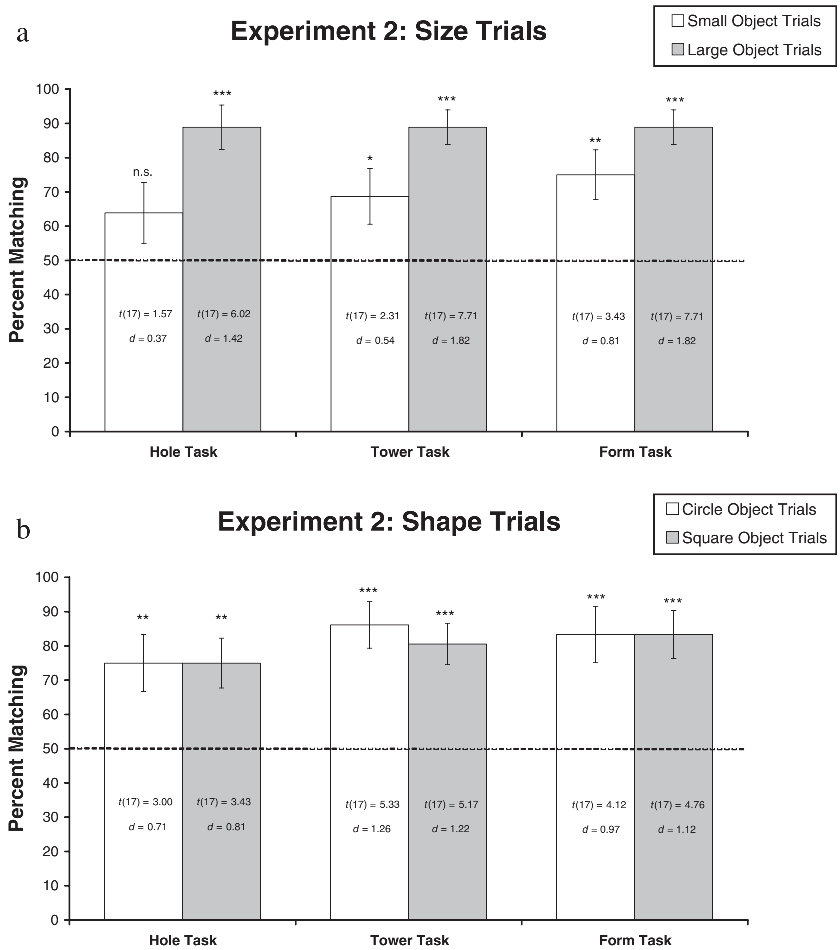

Figure 4. Performance on (a) size and (b) shape trials by children in Experiment 2.
Note. Error bars represent the standard error. Asterisks indicate bars that are significantly different from chance.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Experiment 1, providing evidence that children in the first half of the 3rd year succeed at the hole-fitting task not only when objects have the simplest and most symmetrical shapes (the sphere and cube from Experiment 1) but also when object shapes are more complex (elongated cylinders and rectangles). Moreover, 25- to 30-month-old children mastered the related tasks of stacking blocks to build a tower and placing a block on a surface so as to cover a two-dimensional form exactly. Because all three of these tasks depend on an analysis of the shapes of three-dimensional objects and their surfaces, children's performance suggests that abilities to perform these analyses are fairly well established by the 3rd year of life.

In retrospect, aspects of the data from the size trials suggest that children's interpretation of the task presented on these trials did not consistently accord with our expectations. Children's size trial performance on the tower and form tasks suggests that our task manipulation, emphasizing the covering of the pink surface, worked to some degree: Children reliably placed the small object on the small form or tower even though it could fit on both bases. Nevertheless, children did not reliably place the small object in the small hole. Because they successfully matched objects to apertures on shape trials in the hole task, their failure to do this on size trials in the hole task cannot plausibly be attributed to a failure to represent the relevant object properties. Instead, it is likely that children misinterpreted the task instructions on these trials. Because the pink surface was less visible at the bottom of the apertures than at the base of the tower or paper, children may have felt they could ''make the pink spot'' disappear on hole trials by inserting objects of either size.

A final limitation of Experiment 2 concerns the high level of performance that children exhibited. In general, the 25- to 30-month-old children in this experiment performed all of the tasks quite well. In the last experiment, therefore, we presented the same tasks to younger children.

Experiment 3

Children aged 18–24 months were tested on the hole, tower, and form-fitting tasks of Experiment 2. The method was the same as in Experiment 2, except in one respect. Piloting revealed that younger children performed the session quite slowly. Because the full experiment was quite lengthy and tried children's patience, we reduced the study to 18 trials and presented two rather than four size trials in each task. Half the children were given size trials with the two small objects (one of each shape), and the others were given size trials with the two large objects (one of each shape).

Method

The participants were 48 children ranging in age from 18.7 to 23.4 months (25 females; mean age = 21.2 months, SD = 1.4 months). Eighteen additional children were tested, but excluded from analyses because they did not complete all the trials. A second coder scored the sessions of 12 children for reliability. The coders agreed on 100% of trials. Preliminary analyses revealed no effects of participant gender or task order; therefore, the data were collapsed over these variables in the analyses reported below.

Results

An ANOVA with task (hole, tower, and form) and trial type (size and shape) as within-subject factors revealed no effect of task, $F(2, 94) = 2.33$, *ns*, $\eta_p^2 = .05$; no effect of trial type ($F < 1$); and no interaction of Task × Trial Type, $F(2, 94) = 2.39$, *ns*, $\eta_p^2 = .05$.

Size trials. An ANOVA with task (hole, tower, and form) as a within-subject factor and object size (small object and large object) as a between-subject factor revealed only a significant effect of object size: As in Experiment 2, children were more likely to pick the endpoint that matched the object's size on large object trials than on small object trials, $F(1, 46) = 4.78$, $p < .05$, $\eta_p^2 = .09$. There was no effect of task, $F(2, 92) = 1.55$, *ns*, $\eta_p^2 = .03$, and no interaction of Task × Object Size, $F(2, 92) = 2.36$, *ns*, $\eta_p^2 = .05$.

In the hole task, children chose the base that matched the object on 40% of small object size trials, $SD = 33$, $t(23) = -1.55$, *ns*, $d = 0.32$, and 65% of large object size trials, $SD = 31$, $t(23) = 2.29$, $p < .05$, $d = 0.47$. On size trials in the tower task, children chose the matching base on 56% of small object trials, $SD = 27$, $t(23) = 1.14$, *ns*, $d = 0.23$, and 67% of large object trials, $SD = 24$, $t(23) = 3.39$, $p < .01$, $d = 0.69$. In the form task, children chose the base that matched the object on 56% of small object trials, $SD = 22$, $t(23) = 1.37$, *ns*, $d = 0.28$, and 58% of large object size trials, $SD = 35$, $t(23) = 1.16$, *ns*, $d = 0.24$ (see Figure 5a).

Shape trials. An ANOVA with task (hole, tower, and form) and object shape (circular vs. square) as within-subject variables revealed a main effect of task, $F(2, 94) = 3.93$, $p < .05$, $\eta_p^2 = .08$. Post hoc comparisons indicated that children's performance on shape trials in the form task exceeded their performance on shape trials in both the hole task (Tukey's HSD, $p < .05$) and the tower task (Tukey's HSD, $p < .05$); children's performance in the hole and tower tasks did not differ. There was no significant effect of object shape, $F(1, 47) = 2.54$, *ns*, $\eta_p^2 = .05$, and only a marginal interaction of task and object shape, $F(1, 47) = 2.52$, $p = .09$, $\eta_p^2 = .05$. Children chose the base that matched the target object on 56% of shape trials in the hole task, $SD = 27$, $t(47) = 1.63$, *ns*, $d = 0.24$; 57% of shape trials in the tower task, $SD = 23$, $t(47) = 1.99$, $p = .052$, $d = 0.29$; and 66% of shape trials in the form task, $SD = 21$, $t(47) = 5.34$, $p < .001$, $d = 0.77$ (see Figure 5b).

Discussion

What do the findings from Experiment 3 tell us about sources of young children's difficulty in hole-fitting tasks? First, children made reliably more errors on shape trials in the hole task than on shape trials in the form task despite the fact that the critical object shape remained visible on both these tasks. These two tasks also involved the same objects and very similar gestures of placing an object on top of a two-dimensional visual display, but the critical difference between them was that the base shape was formed by a negative space in the hole task and a positive space in the form-fitting task. Children's superior performance on the form task, relative to the hole task, suggests that part of the difficulty with

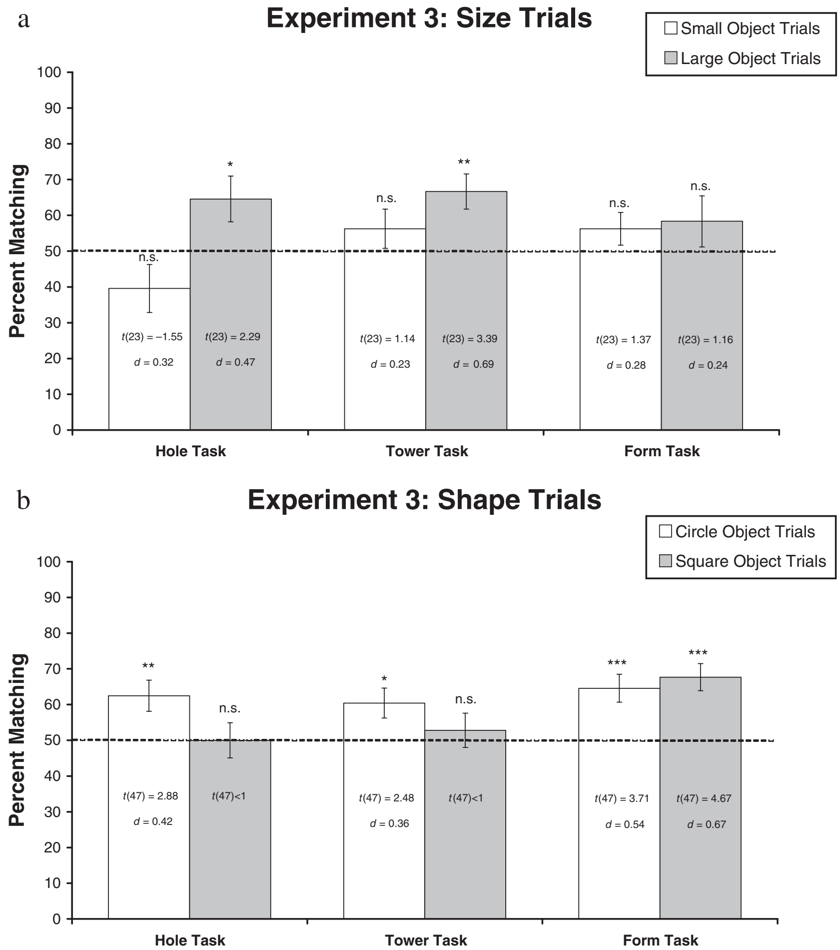

Figure 5. Performance on (a) size and (b) shape trials by children in Experiment 3.
Note. Error bars represent the standard error. Asterisks indicate bars that are significantly different from chance.
$^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

hole-fitting tasks stems from the requirement that the shapes of positive and negative spaces be matched.

Performance on the size trials further supports this suggestion because children performed equally on the form and hole tasks when size was the relevant dimension. Although the shape descriptions of an object and a hole differ because they are parsed into parts at different locations, the size descriptions of an object and hole should not differ because object parsing is invariant over size transformations (Feldman & Singh, 2005). Children's performance therefore suggests that the greater difficulty of the hole task, relative to the form task, stems not from general differences between the two tasks (such as the difference between placing one object *in* vs. *on* another) but rather from the specific difficulty of relating the shapes of positive and negative spaces.

If difficulty relating positive and negative spaces were the only factor responsible for children's difficulty with hole-fitting tasks, however, children should have performed well on shape trials in the tower task. To the contrary, children's performance on shape trials in the tower task was not different from chance and was reliably worse than performance on shape trials in the form task.

A comparison of children's performance on shape trials in the form and tower tasks therefore suggests a second source of difficulty for children. Although children performed similarly on these two tasks when the relevant object variable was size, they performed reliably better on the form task when the relevant object variable was shape. Because the form and tower tasks are extremely similar, this difference may have stemmed from a tendency to analyze the shapes of the three-dimensional bases in the tower task and compare them to the target object. Although adults are highly sensitive to the shapes of two-dimensional forms, we have difficulty processing shape information in three-dimensional objects (Pani, 1997; Tarr, 1995). Thus, the young children in Experiment 3 may have found it easier to match an object shape to a base shape when the critical shape information was exhibited by a two-dimensional form (in the form task) and did not need to be extracted from a three-dimensional object (in the tower task).

Experiment 3 provides no evidence for mental rotation as a source of difficulty for children. Children performed no better on size trials, which required no mental rotation in the present experiments, than on shape trials, for which mental rotation was required. Moreover, children showed only a nonsignificant tendency to perform better with the round object than with the square object despite the greater demands of mental rotation posed by the latter objects. It is possible, therefore, that the demands of mental rotation did not contribute to children's difficulty in the present tasks. Alternatively, mental rotation may have posed difficulties for the children that the present experiments failed to clarify because the object properties that we manipulated exerted only small effects on the relevant task demands. In every trial of Experiments 2 and 3, children were required to rotate an object to place it on a base: The task and shape manipulations influenced only the extent and precision of the rotation that was required. Consistent with the thesis that difficulties with mental rotation hinder young children's object manipulations, Örnkloo and von Hofsten (2007) found that while 22-month-old children were quite successful with both cylindrical and square blocks when trying to insert a single object into a fitting hole, 18-month-old children were only successful with cylindrical blocks. Additional research with younger and older children therefore is necessary to clarify the role of mental rotation in children's performance on hole-fitting tasks.

General Discussion

In three experiments, we take a new look at an old and well-known developmental phenomenon. Children's difficulty fitting blocks into holes is striking because children's errors are so easy for adults to see. To an adult, it is obvious that a round peg does not fit into a square hole. Why do young children fail to appreciate this fact? Attempts to account for this problem have typically focused on cognitive differences between adults and children: Children might fail to perceive or represent objects in the ways that adults do, they might fail to remember objects that disappear from view, or they might fail to construct or execute appropriate action plans. In contrast, our findings suggest that other perceptual and cognitive factors—including factors that limit the performance of adults on more complex tasks of object perception and representation—pose challenges for children confronted with seemingly simple hole-fitting tasks. In the absence of a long history of learning about particular kinds of objects and their projective spatial properties, hole-fitting relations might be no more obvious to adults than they are to young children.

The findings of the present experiments provide evidence that children have trouble relating the shapes of positive and negative spaces, as do adults (e.g., Bertamini & Croucher, 2003). Moreover, the findings suggest that children have difficulty representing and relating the silhouettes of the shapes of three-dimensional shapes, again like adults (e.g., Pani, 1997). Taken as a whole, the pattern of data suggests that multiple factors contribute to children's performance on tasks of object representation and goal-directed action (Keen & Shutts, 2007). Additional research is necessary to clarify and illuminate factors that limit children's success on hole-fitting tasks, as well as the ways in which children's errors on hole-fitting tasks relate to other perception and action coordination problems common to children of the ages tested here (e.g., Brownell, Zerwas, & Ramani, 2007; DeLoache, Uttal, & Rosengren, 2004). Future research could also profitably examine children's placement and adjustment strategies in order to gain insight into processes involved in successful (and unsuccessful) object-fitting behaviors.

One robust finding from the present experiments is that by 30 months of age, children performed quite well on our object relation tasks. There are several possible reasons for their success. First, children over this age range develop knowledge about specific, familiar object shapes such as cubes and spheres, and their affordances for building complex structures. This knowledge may allow children to select and manipulate familiar objects appropriately without the need for detailed processing of their three-dimensional structure. Second, children acquire terms in their native language for object kinds (e.g., *block*, *tower*), actions (e.g., *build*, *fit*), and spatial relations (e.g., *in*, *on*). These words may both call attention to the relevant object properties and relations, and may allow for more efficient encoding of those properties and relations. Third, children in the communities that we studied gain specific experience with the kinds of tasks that we presented through play at home and in preschool with blocks, puzzles, and pictures. Future research is needed to test each of these possibilities. All these possibilities are consistent with the idea, however, that developmental changes on the present tasks are rooted in the acquisition of knowledge of particular kinds of objects and their relations, rather than from changes in the fundamental processes by which objects are represented.

The present findings have more general implications for research on visual cognition in adults and children. If common constraints on visual processing apply to children and to adults, then studies of those constraints in adults can shed light on developmental changes in children's capacities. The present research was guided by three discoveries from the field of adult visual cognition: that adults have difficulty representing shape information in three-dimensional objects (e.g., Pani, 1997), that adults give different descriptions to the shapes of negative and positive spaces (Baylis & Driver, 1995; Bertamini & Croucher, 2003; Driver & Baylis, 1995; Hoffman & Singh, 1997), and that adults have difficulty with tasks requiring mental rotation (Cooper & Shepard, 1984). The present findings—in particular, those from Experiment 3—suggest that young children share the first two of these difficulties. These difficulties partially account for young children's failures in object manipulation tasks.

If common processes underlie object representations in adults and young children, then studies of children also may shed light on mature processes of visual cognition. When we as adults fit a cork into a bottle or a peg into a hole, it is tempting to think that we do so by virtue of a fully general and flexible analysis of objects and their spatial relations. The present findings, together with research in visual cognition, suggest instead that our usually smooth and flexible object manipulations depend in part on a vast array of acquired knowledge about particular objects, actions, and spatial relations. Young children may perform truly general and inventive analyses of objects and their spatial and mechanical relations more often than adults, who possess specific knowledge that allows them to bypass these processes.

References

Bayley, N. (1969). *Bayley Scales of Infant Development*. New York: Psychological Corporation.

Baylis, G., & Driver, J. (1995). One-sided edge assignment in vision: 1. Figure-ground segmentation and attention to objects. *Current Directions in Psychological Science*, *4*, 140–146.

Bertamini, M., & Croucher, C. J. (2003). The shape of holes. *Cognition*, *87*, 33–54.

Brownell, C. A., Zerwas, S., & Ramani, G. B. (2007). ''So big'': The development of body self-awareness in toddlers. *Child Development*, *78*, 1426–1440.

Cooper, L. A., & Shepard, R. N. (1984). Turning something over in the mind. *Scientific American*, *251*, 106–114.

DeLoache, J. S., Uttal, D. H., & Rosengren, K. S. (2004). Scale errors offer evidence for a perception-action dissociation early in life. *Science*, *304*, 1027–1029.

Driver, J., & Baylis, G. (1995). One-sided edge assignment in vision: 2. Part decomposition, shape description, and attention to object. *Current Directions in Psychological Science*, *4*, 201–206.

Feldman, J., & Singh, M. (2005). Information along contours and object boundaries. *Psychological Review*, *112*, 243–252.

Gesell, A., & Thompson, H. (1934). *Infant behavior: Its genesis and growth*. New York: McGraw-Hill.

Hayashi, M. (2007). Stacking of blocks by chimpanzees: Developmental processes and physical understanding. *Animal Cognition*, *10*, 89–103.

Hayashi, M., & Matsuzawa, T. (2003). Cognitive development in object manipulation by infant chimpanzees. *Animal Cognition*, *6*, 225–233.

Hoffman, D. D., & Richards, W. (1984). Parts of recognition. *Cognition*, *18*, 65–96.

Hoffman, D. D., & Singh, M. (1997). Salience of visual parts. *Cognition*, *63*, 29–78.

Hood, B. M., Cole-Davies, V., & Dias, M. (2003). Looking and search measures of object knowledge in pre-school children. *Developmental Psychology*, *39*, 61–70.

Keen, R., & Shutts, K. (2007). Object and event representation in toddlers. *Progress in Brain Research*, *164*, 227–235.

Kelly-Vance, L., Needelman, H., Troia, K., & Oliver Ryalls, B. (1999). Early childhood assessment: A comparison of the Bayley Scales of Infant Development and play-based assessment in two-year-old at risk children. *Developmental Disabilities Bulletin*, *27*(1), 1–15.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*, 940–949.

Mash, C., Novak, E., Berthier, N. E., & Keen, R. (2006). What do two-year-olds understand about hidden-object events? *Developmental Psychology*, *42*, 263–271.

McKenzie, B., Slater, A., Tremellen, S., & McAlpin, S. (1993). Reaching for toys through apertures. *British Journal of Developmental Psychology*, *11*, 47–60.

Meyer, E. (1940). Comprehension of spatial relations in preschool children. *Journal of Genetic Psychology*, *57*, 119–151.

Örnkloo, H., & von Hofsten, C. (2007). Fitting objects into holes: On the development of spatial cognition skills. *Developmental Psychology*, *43*, 404–416.

Örnkloo, H., & von Hofsten, C. (in press). Young children's ability to solve spatial problems involving a choice. *European Journal of Developmental Psychology*.

Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

Pani, J. R. (1997). Descriptions of orientation in physical reasoning. *Current Directions in Psychological Science*, *6*, 121–126.

Pani, J. R., Jeffres, J. A., Shippey, G. T., & Schwartz, K. J. (1996). Imagining projective transformations: Aligned orientations in spatial organization. *Cognitive Psychology*, *31*, 125–167.

Peterson, M. A. (2003). On figures, grounds, and varieties of amodal surface completion. In R. Kimchi, M. Behrmann, & C. Olson (Eds.), *Perceptual organization in vision: Behavioral and neural perspectives* (pp. 87–116). Mahwah, NJ: Erlbaum.

Rock, I. (1974). The perception of disoriented figures. *Scientific American*, *230*, 78–85.

Rubin, E. (1921). *Visuaell wahrgenommene figuren* [Figure and ground]. Copenhagen: Glydenalske Boghandel.

Tarr, M. J. (1995). Rotating objects to recognize them: A case study on the role of viewpoint dependency in the recognition of three-dimensional objects. *Psychonomic Bulletin & Review*, *2*, 55–82.

Tarr, M. J., & Bülthoff, H. H. (1995). Is human object recognition better described by geon structural descriptions or by multiple views? Comment on Biederman and Gerhardstein (1993). *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 1494–1505.

Tarr, M. J., & Bülthoff, H. H. (Eds.). (1998). Image-based object recognition in man, monkey and machine. In *Object recognition in man, monkey, and machine* (pp. 1–20). Cambridge, MA: MIT Press.