SHAPES WITHIN SHAPES: RELATING NEGATIVE SPACE TO POSITIVE SPACE

IN OBJECT PERCEPTION AND FITTING TASKS

AN ABSTRACT

SUBMITTED ON THE TWENTY-SIXTH DAY OF JANUARY 2018

TO THE DEPARTMENT OF PSYCHOLOGY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

OF THE SCHOOL OF SCIENCE AND ENGINEERING

OF TULANE UNIVERSITY

FOR THE DEGREE

OF

MASTER OF SCIENCE

BY

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APPROVED:

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Abstract

The development of relating negative space to positive space was examined in children between 18 and 36 months of age (N = 64). Children were presented with a series of compound objects, shapes embedded in shapes, and asked to match the inner aperture of the object to a corresponding tower. The results revealed that matching the negative space of an aperture to the positive space of another object is difficult even for the oldest children. This difficulty was influenced by the shape of the compound object, specifically the shape of the inner aperture in relation to the shape of the solid surround. The current study provides new information about the ability of children to solve fitting tasks.

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Introduction

In daily life, we encounter tasks that require relating negative space to positive space. When we place a new paper towel roll onto its holder, put the tops back on bottles or containers, position the holes of a shower curtain to hang it on the shower rod, and fit nuts on bolts, we are matching negative space to positive space. But, what are the spatial requirements for relating actions to spaces in our everyday worlds? While most work on fitting has been focused on relating positive space to negative space (Jung, Kahrs, & Lockman, 2015; Örnkloo & von Hofsten, 2007; Shutts, Keen, Örnkloo, von Hofsten, & Spelke, 2009), much less emphasis has been placed on the spatial relationship of fitting objects with holes onto solid objects. When matching an object that contains an aperture (negative space) to another object (positive space), children must relate the shape of the aperture to the shape of the second object, while inhibiting responses to the solid shape that surrounds the aperture. To date, the influence of the shapes of objects and apertures in relation to one another in tasks that require matching negative space to positive space has not been systematically examined. Investigating the ways in which toddlers relate negative space to positive space can provide insight into the developmental trajectory of the relationship between holes and solid objects, thereby adding to our current understanding of children's spatial perception abilities.

In young children, spatial ability is an umbrella term that encompasses the ways in which children think about, mentally manipulate, and act upon space in their environments (Erlich, Levine, & Goldin-Meadow, 2006; Verdine et al., 2014). One key component of spatial development is shape perception, which begins to develop in early infancy (Milewski, 1976; Slater, Morison, & Rose, 1983; Yonas & Granrud, 1985). Shape recognition is an important first step in young children's early understanding of the properties of objects. As children begin to recognize these properties, they can adaptively construct the ways in which they act on objects. The way children act on objects, or relate objects, can offer insights into young children's spatial understanding. During the first and second years, children become increasingly interested in the ways in which objects relate to one another (Gesell, Amatruda, & Thompson, 1934; Örnkloo & von Hofsten, 2007; von Hofsten, 2007, 2009), and this can be seen in the behavior of young children, as they begin to explore how objects fit together (Gesell et al., 1934). Not only is fitting objects together an adaptive ability, but it is also believed to lay the groundwork for early mathematical abilities and has been shown to impact academic outcomes, particularly in STEM fields (Grissmer et al., 2013; Newcombe, 2010; Verdine et al., 2014).

Past research has examined the development of matching objects to apertures. Collectively, the existing body of object fitting research suggests that children are able to correctly fit objects to apertures between 20 and 24 months of age (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Shutts et al., 2009). These tasks, however, all examine matching positive space (an object) to negative space (an aperture). In contrast, the development of the ability to match apertures to objects is not as well understood.

Early Shape Recognition

To begin to understand the ways children relate negative space and positive space, it is important to first look at the development children undergo in their ability to understand the spatial properties of objects, such as form or shape. Shape perception is thought to begin in early infancy and then undergo developmental shifts, becoming more advanced in the first year. There is some evidence that shape perception in its most basic form is actually present at birth. Using habituation procedures, Slater and colleagues (1983) found that newborn infants, ranging from 7- hours- to 9-days-old, demonstrated preferential attention to novel shapes when presented adjacent to a different, familiar shape. These results suggest that newborns are able to discriminate between different shapes.

It would seem infants are able to then build on this early ability, and in the first few months develop more complex shape recognition abilities. For example, previous research has investigated infants' sensitivity to internal and external pattern changes within a stimulus. One- and 4-month-olds were shown two dimensional pictures of one shape (circle, square, or triangle) centered within another shape. Shifts in either the external, internal, or both shapes were then presented. Four-month-olds demonstrated sensitivity to changes in both internal and external shapes, while 1-month-olds showed sensitivity to changes that only affected the external shape (Milewski, 1976). These results suggest younger infants only perceive the external shape when one shape is embedded in another. By the fourth month, there appears to be a developmental shift tied to attention, allowing for the perception of both the internal and external shapes.

As infants approach the second half of the first year, shape perception abilities continue to develop and become more advanced. When surfaces with convexity and concavity as well as pictures using different shading to depict convexity and concavity were shown to 7-month-olds, infants preferentially reached for the convex surface, demonstrating a perceptual understanding for information about three-dimensional shape (Yonas & Granrud, 1985). Further, the concavity represented in this study is negative space, suggesting perceptual information about negative space is available beginning as young as 7 months.

Collectively, these studies suggest that the developmental trajectory of shape perception begins at birth, with newborns able to discriminate between different shapes. By the fourth month, infants are then able to perceive differences in both the internal and external properties of compound shapes. Shape perception advances further by the seventh month, as infants begin to demonstrate an understanding of three-dimensional negative space. However, it remains unclear how the perception of three-dimensional negative space changes when it becomes embedded in a solid surround. When negative space is embedded in a solid surround, there is often discrepancy between the forms created by the negative space and the solid surround. This conflicting three-dimensional space may influence children's ability to act on objects early in development.

Object Properties and Object Relations

As children begin to explore object function (i.e., playing with puzzles, experimenting with putting objects into holes, sorting shapes), they can build on the shape perception that begins in infancy to develop a deeper understanding of an object's more complex properties and begin to relate objects to one another.

During the first two years of life, developmental changes in visual object recognition, object name, and category learning occur (Pereira, James, Jones, & Smith, 2010). These changes, which are an important aspect of higher-ordered understanding of shapes and their functions, are supported in part by the child's ability to mentally represent objects using a visual frame of reference. For example, when three-dimensional objects are presented in unfamiliar positions or from unfamiliar viewpoints, it is difficult, even for adults, to recognize certain properties of objects, especially object shape. A visual point of reference is often required to compensate for this difficulty in shape recognition (Tarr, 1995).

One such visual frame of reference that allows children to mentally represent a three-dimensional object's shape is the axis of elongation, which is an object's primary longest axis. When children hold objects by the axis of elongation, such that the axis of elongation is perpendicular to their line of sight, the resulting viewpoint provides the child with additional visual information about an object's properties, especially an object's shape (Smith, Street, Jones, & James, 2014). Research suggests that by the 24th month, children are able to align the axes of elongation of objects and apertures, demonstrating that the information provided about an object's properties is directly related to the ability to act on the object (Pereira et al., 2010; Smith et al., 2014). This suggests that the higher-order and more advanced understanding of object properties that is occurring during the first two years would, in turn, support a child's developing ability to act on objects.

Object alignment is of these developing action abilities. Aligning objects requires more advanced shape recognition, in that the shape of one object in relation to the shape of another object must be understood to successfully align the objects. In a study assessing infant chimpanzee block stacking behaviors, Hayashi (2007) found that young chimpanzees do have the ability to relate objects to one another. It was suggested that in tasks that require combining two objects, such as stacking cylindrical blocks on top of one another, the physical properties of each object must be understood, both individually and in relation to one another.

Aligning objects also requires relating multiple properties of objects. Research conducted by Fragaszy, Stone, Scott, and Menzel (2015) with 2-, 3-, and 4-year-olds investigated children's ability to insert either symmetrical (e.g., cross shaped bar) or asymmetrical objects (e.g., tomahawk shaped bar) into apertures, and found children were more easily able to align the symmetrical objects. Because asymmetrical objects have more different features properties than symmetrical objects, the results suggest that children are able to more easily align and fit shapes with fewer features. These findings are consistent with work on non-human primates, as primates also have difficulty aligning and fitting objects with multiple features (Fragaszy, Kuroshima, & Stone, 2011). This difficulty in aligning objects with multiple features demonstrates that accurate alignment increases in difficulty as the number of spatial relations increase. Aligning an object to an aperture requires children to conceptualize multiple spatial relations concurrently, rather than a single spatial relation, which may account for this difficulty. The ability to conceptualize these multiple spatial relations requires an understanding of how the objects relate to one another.

Neural Basis of Object Relation

Relating objects to other objects is a visuomotor process, and some suggest this involves two structurally distinct neural systems for vision (i.e., ventral stream, dorsal stream), each developing at different rates (Dilks, Hoffman, & Landau, 2008; Milner & Goodale, 1995). The ventral stream, known as the vision for perception system, allows for the perception of an object's properties (i.e., shape, size, location) and is thought to be more developed in toddlers than the dorsal stream (Johnson, Mareschal, & Csibra, 2001). The dorsal stream, known as the vision for action system, is responsible for acquiring visual information for targeted actions (Milner & Goodale, 2008, 1995; Smith et al., 2014; Street, James, Jones, & Smith, 2011).

Past research has examined the presence of these two distinct visual systems. In a study by van Wermeskerken, van der Kamp, Savelsbergh, and von Hofsten (2013) with 6- and 7-month-olds, identical objects were presented at different physical distances from one another or at different perceptual distances from one another. Perceptual distance was created by placing identical objects in front of two different texture gradient backgrounds, which results in one object appearing closer than the other object. Infants' preferential reaching was affected only by an object's physical distance, while perceptual distance, created by the illusion of distance, did not influence reaching. This suggests support for a two-visual system being present as early as the first year of life.

Research has also addressed when these two streams integrate. In a study investigating the ways in which children relate objects to one another, 18- to 24-month-old children were presented with a set of alignment tasks (Street et al., 2011). The first required children to fit their hands through a slot, which children of all ages were able to do correctly. The second task had children correctly align an object for insertion into a slot, which requires coordinating planned actions based on the properties of the objects. Children were not able to successfully complete this object alignment task until the 24th month, suggesting the two visual streams may begin to work in tandem around two years of age.

Despite these suggestions, it is important to note the interconnectedness of perception and action in object relational tasks. Action involves perception, as a child must perceive an object's properties (i.e., shape, size, and location of the target). Acting on the target aids perception, as visual information, in conjunction with haptic feedback gained from the action, leads to a better understanding of the properties of objects (Antrilli & Wang, 2016). The aforementioned research may not have fully considered the reciprocal relationship between the perception of an object's properties and the associated planned actions, with each influencing and aiding the other.

Relating Positive and Negative Space

Relating positive and negative space is an important aspect of the reciprocal relationship between perception and action. The ability to relate positive space (an object) to negative space (an aperture) has traditionally been studied through the use of shape-sorting tasks. Pioneering work on fitting objects into holes showed that at 18-months-old, children were unable to relate objects to corresponding apertures, but during the first half of the second year, children became more proficient with this task (Meyer, 1940). Consistent with this earlier research, the current literature has examined the ways in which young children relate positive space to negative space through the use of fitting tasks that require children to fit an object into an aperture. Collectively, this research suggests the ability to fit objects into apertures develops late in the second year of life (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Shutts et al., 2009).

In a study with 16- to 33-month-old children, Jung, et al. (2015) examined the ability to fit a rod, oriented either vertically or horizontally, into a slot, also positioned either vertically or horizontally. The results suggest children are able to successfully fit the positive space of the rod into the negative space of the slot by the 24th month. Consistent with these findings, Shutts et al. (2009) presented groups of 15- to 36-month-old children with a series of fitting tasks. One task required the children to fit circular and square objects into circular or square shaped apertures, which were cut into the top of a solid wooden box. In doing so, they found that by 24-months- old, the majority of children were performing significantly above chance and correctly fitting the positive space of the object into the negative space of the aperture.

In a similar task, Örnkloo and von Hofsten (2007) presented 14- to 26-month-old children with a small wooden box containing circular, triangular, and square shaped apertures. Children were tasked with inserting objects, also circular, triangular, and square shaped, into the aperture of the matching shape. The results showed that children began solving the fitting task consistently at 22 months of age.

Collectively, the research suggests that children are able to select the correct shape and match or fit the shape to the aperture, thereby successfully relating positive space to negative space, between 20 and 24 months. However, the current literature examined matching objects to apertures. To date, research has not examined the development of matching apertures to objects, which may have a different trajectory than the reverse because of difficulties that could arise from an increased complexity of the task.

The tasks used in the fitting literature involved relatively simple aperture and object shapes, and changes in the complexity of the shapes could influence the developmental trajectory previously observed. For example, past research has demonstrated that when the complexity of the shape of an object increases, children as old as 3 years have shown difficulties in correctly matching an object to an aperture (Meyer, 1940). Objects and apertures that are comprised of squares and triangles, rather than circles, may influence children's ability to successfully match an object to an aperture. In the fitting study performed by Shutts et al. (2009), results indicated younger children were able to correctly fit circular objects into apertures more often than cube shaped objects. Circles are less complex than other shapes, as there are no angles or intersections to account for. An object's shape complexity, therefore, likely influences the ability to relate the object to an aperture.

Compound objects. The introduction of a complex compound object may also increase difficulty, thereby influencing the developmental trajectories previously observed. Negative space (the aperture) always exists within positive space, creating a compound object with two distinct shapes: The shape of the solid surround and the shape of the inner aperture. The combination of a shape within a shape results in multiple contours, as well as potentially conflicting information between the shape of the aperture and the shape of the solid surround, each of which must be accounted for in matching tasks.

In the fitting study performed by Örnkloo and von Hofsten (2007), children successfully fit squares more often than isosceles and right triangles into the square-shaped box. In contrast to square apertures presented within a square box, triangular apertures presented within a square box create conflicting information between the outer shape of the box and the inner contour of the hole. Although the authors assert that the findings can be explained by differences in shape, it is not clear if the difficulties exhibited in fitting the triangles compared to the squares can be solely attributed to the more complex shape of the triangle. It may be that the conflicting space created by the triangular aperture in relation to the square-shaped outer object also contributes to this difficulty.

Conflicting shape information must also be accounted for to successfully complete some object matching tasks. Sera and Millett (2001) presented novel cone and wedge shaped objects, each with a smaller secondary piece that could be attached, to children and adults. Children younger than 4 years did not recognize the shapes of the primary cone and wedged shaped objects when the secondary piece was attached. This suggests that while older children and adults are able to inhibit certain irrelevant aspects of shape properties, children younger than 4 use all aspects of the perceptual information available. Collectively these findings suggest that with complex objects (i.e., shape within a shape), younger children may struggle with conflicting shape information and may be unable to inhibit the outer contour of an object to focus on an inner aperture's shape.

Effect of aperture. The aperture itself can add complexity, as children may not represent apertures as having a distinct shape, and instead view the aperture as an expansion of the surrounding surface. Consistent with this argument, Bertamini and Croucher (2003) suggest that positive and negative spaces are represented differently depending on circumstance. The shape of a hole, for example, is only available indirectly from the shape of the surrounding object. This suggests that when negative space is embedded in a shape, the external shape may affect the representation of the internal negative space. The role of the solid surround and its relationship to an inner aperture, however, has not been directly investigated in work on the development of fitting.

It is unknown if the different types of conflicting space arising from an aperture embedded in a solid object affects a child's ability to represent negative and positive spaces. The congruency between the shape of the hole and the solid surround of a compound object may influence a child's ability to then use the compound object to act on a second object. Specifically, a child's ability to fit an object into an aperture could be influenced by the shape of the aperture in relation to the shape of the solid surround in which it is embedded. In the current literature, the potential influences that congruent and incongruent compound shapes may have on children's actions in fitting tasks has not been systematically examined, resulting in an incomplete picture of the developmental processes involved in relating positive and negative space.

The Current Study

In object fitting tasks, when matching an object that contains an aperture (negative space) to another object (positive space), children must relate the shape of the aperture to the shape of the second object, while inhibiting responses to the solid shape that surrounds the aperture. By systematically varying the shape of both the aperture and the solid surround, the process by which children match negative space to positive space, as well as the ways in which conflicting space (i.e., incongruent inner apertures and solid surrounds) may influence action can be examined.

To examine the developmental progression of matching an aperture to another object, children between the ages of 18 and 36 months participated in an object fitting study. Each child was presented with a three tower board and a one tower board (see Figures 1 & 2), as well as a series of objects constructed around all possible combinations of a circle, square, or triangle aperture embedded in a circle, square, or triangle solid shape (see Figure 3). Using the three tower board (tower selection condition), children were presented with one compound shape stimulus at a time and selected the tower on which it would fit (see Figure 4a). Using the one tower board (object selection condition), children were presented with three compound shape stimuli at a time and selected which of these objects would fit on the tower (see Figure 4b). Thus, in the tower selection condition children were selecting amongst positive space exemplars (the towers), and in the object selection condition children were selecting amongst negative space exemplars (the inner aperture of the compound shape). Because negative space may be more difficult for children to perceive and act on, we expected that selecting amongst negative space exemplars (one tower condition) would be more difficult than selecting amongst positive space exemplars (three tower condition).

Based on the suggestion of two distinct visual streams, one for perception and one for action (Milner & Goodale, 2008, 1995), past fitting work has attempted to examine the two streams separately. However, in some instances, researchers have not been able to fully isolate action from perception. For example, the Street et al., (2011) study argues for the integration of the two visual streams based on the findings that 18-month-old and 24-month-old children can align and fit their hand through a slot, while only 24-month-olds can align and fit an object through the slot. However, both tasks involve coordinating and planning actions based on perceptual information. In this instance, vision for perception and vision for action may not have been truly isolated. The current study attempted to examine the visual streams in such a way that the perception task was not inadvertently employing vision for action, and the action task accurately represented the combination of perception and action that must co-occur to fit apertures on objects.

To accomplish this, each child completed both a perception task and an action task. The tasks required children to match each object's interior shape to the corresponding tower by pointing to the correct match (perception only task) and by physically fitting the aperture onto the corresponding tower (action task). By removing action in one condition and retaining action in the second condition any possible discrepancies in ability across the two tasks could be examined. Past fitting work suggests that differences between the perception and action tasks would be obtained in the current study (Street et al., 2011; van Wermeskerken et al., 2013).

Nevertheless, some of the findings suggesting differences in perception and action tasks conflict with other studies in the developmental literature. For example, as previously noted, van Wermeskerken et al. (2013) found that 6- and 7-month-olds' preferential reaching was only influenced by physical distance and not perceptual distance created by texture gradients. But these results do not line up with findings from Yonas, Granrud, Arterberry, and Hanson (1986) who argue that the ability to perceive depth from texture gradients develops at 7 months, based on findings that 7-month-olds do preferentially reach for an object that appears perceptually closer through the use of a texture gradient illusion. Further, it has been shown that between 5- and 7-months-old, binocular depth cues supersede pictorial depth cues (Yonas & Granrud, 1985). Without testing the infants in a monocular condition, van Wermeskerken and colleagues (2013) may not have effectively tapped into perceptual distance, making it unclear whether the findings are truly representative of infants' ability to perceive distance or truly indicative of two distinct and separate vision systems.

Based on these discrepancies, was unclear whether differences between the perception task and action task in the current study would be observed. That said, an object fitting study, with both a perception and action component, that focuses on the influence of external shapes and internal apertures may provide additional insight into the developmental trajectories associated with relating objects to apertures.

Overall, the present study allowed for a systematic investigation of when in development children are able to match negative space to positive space and how congruency of the compound objects' shapes affects children's ability to solve fitting tasks. The aim of the present study was to investigate the following hypotheses: (1) The ability to match negative space to positive space would improve during the toddler period, (2) older children would be better able to inhibit the geometric influence of the solid shape surrounding the aperture when matching the aperture to another object, and (3) children would be more successful when selecting amongst positive space exemplars (tower selection condition) than when selecting amongst negative space exemplars (object selection condition).

The influence of congruency on successful matches was also examined. We expected that, (1) children would match congruent shapes more frequently than incongruent shapes, and (2) the ability to match incongruent shapes would improve with age. Unsuccessful matches were also of interest, as this could provide insight into the ways in which children are conceptualizing complex negative and positive space relations. Thus, the type of error made when unsuccessful matches are selected was examined with the hypotheses that, (1) younger children would select pieces without regard for the outer shape, and (2) older children would make selections consistent with the shape of the solid surround.

Method

Participants

The sample consisted of 64 children (31 females, 33 males) between the ages of 18 and 36 months (see Table 1 for detailed demographics). As seen in Table 1, participants were split evenly across ages. An additional seven children were tested but excluded from the final sample. Three children fussed out, two children only completed one of the two tasks (perception or action), one child only attempted the tower selection board, and one child exceeded the age range. Children were recruited from local preschools, child-centered festivals, and community flyers, and most were tested either at their preschool or at the Infant and Toddler Development Project (26 tested in preschools). Written consent was obtained from a parent prior to child participation in the study. Those who brought their child to the Infant and Toddler Development Project for participation received a gift card to either Wal-Mart or Whole Foods. All methods of recruiting and experimental procedure were approved by the Tulane University Institutional Review Board.

Although there is no standard formula for statistical power in our primary analysis, Generalized Estimating Equations (Diggle, Heagerty, Liang, & Zeger, 2002), past research can be used as a guideline to estimate statistical power for the current study. One prior fitting study examined children ranging from 15-to-30-months old with a sample size of 48 (Shutts et al., 2009). Another fitting study used 53 children, ages 18, 20, and 26 months (Örnkloo & von Hofsten, 2007), while Jung et al. (2015) tested 30 children, ranging in age from 16 to 33 months. These studies yielded sufficiently small standard errors for parameter estimation. The sample size in the present study was increased to ensure sufficient statistical power to detect main effects and interactions.

Table 1

Participant Demographics

Age					Race			Ethnicity		
	n	*M*	*SD*	Range (months, days)		Frequency	Percent	Hispanic (Y/N)	Frequency	Percent
18 months	4	18.39	0.31	17m, 23d - 18m, 27d	White	45	70.30	No	58	90.62
19 months	3	19.36	0.23	19m, 4d - 19m, 22d	More than one	9	14.06	Yes	4	6.25
20 months	3	20.52	0.24	20m, 3d - 20m, 26d	Black	6	9.38	Not reported	2	3.13
21 months	3	21.35	0.22	21m, 1d - 21m, 23d	Asian	2	3.13			
22 months	4	22.54	0.10	22m, 12d - 22m, 25d	Not reported	2	3.13			
23 months	4	23.34	0.20	23m, 0d - 23m, 26d						
24 months	3	24.30	0.27	23m, 27d - 24m, 24d						
25 months	3	25.38	0.14	25m, 4d - 25m, 18d						
26 months	3	26.61	0.15	26m, 8d - 26m, 22d						
27 months	4	27.44	0.11	27m, 3d - 27m, 20d						
28 months	3	28.12	0.16	27m, 25d - 28m, 12d						
29 months	3	29.78	0.35	29m, 1d - 29m, 29d						
30 months	4	30.57	0.06	30m, 12d - 30m, 19d						
31 months	4	31.18	0.12	30m, 28d - 31m, 15d						
32 months	3	32.48	0.32	31m, 26d - 32m, 25d						
33 months	4	33.51	0.12	33m, 6d - 33m, 24d						
34 months	3	34.35	0.23	33m, 26d - 34m, 19d						
35 months	3	35.48	0.13	35m, 6d - 35m, 19d						
36 months	3	36.38	0.33	35m, 23d - 36m, 27d						

Design

In this object fitting study, children were presented with two conditions: a tower selection and object selection board (see Figures 1 & 2). The presentation order of condition was counterbalanced. Within each condition, there was both a perception task, requiring the participant to indicate a selection via pointing, and an action task, requiring the participant to physically match the aperture to the object. The order of task presentation was counterbalanced across participants. The tasks required children to match a series of nine shapes, each with an interior aperture (see Figure 3), with the corresponding tower. These objects were designed to include both congruent and incongruent exterior and interior shapes, and within each task, congruency was randomized. The present study was implemented across a continuous age range, resulting in a cross-sectional 2 (Condition: tower selection vs. object selection) x 2 (Task: perception vs. action) x 2 (Congruency: congruent vs. incongruent) design measuring success, defined by the child making the correct match.

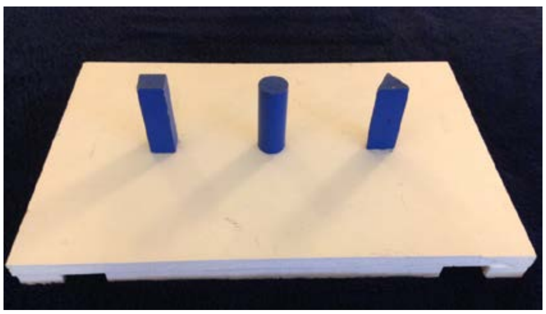

Figure 1. The tower selection condition. Children selected the tower on which the presented stimulus would fit.

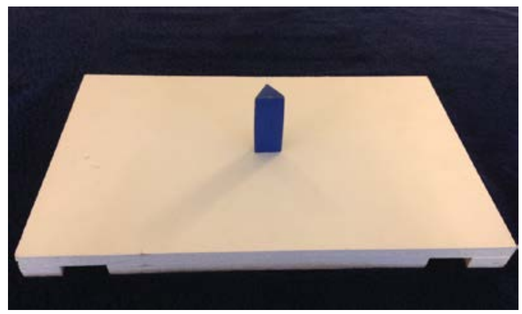

Figure 2. The object selection condition. Children selected the object that would fit.

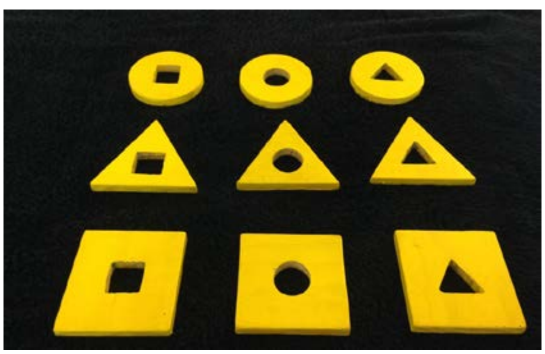

Figure 3. Series of compound objects in which congruency of the inner apertures and solid surrounds systematically varied.

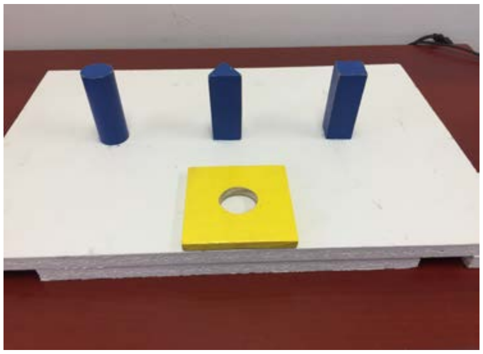

Figure 4a. Tower selection board with trial example.

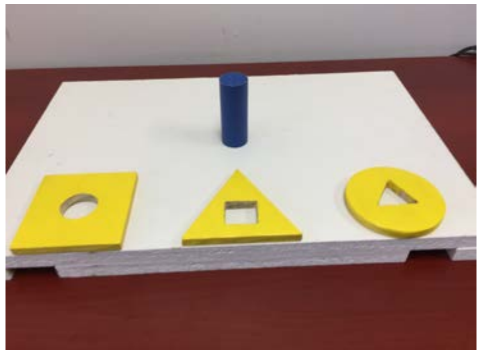

Figure 4b. Object selection board with trial example.

Materials

The boards (see Figures 1 & 2) consisted of a base, 45.72cm x 30.48cm x 3.175cm, constructed out of wood and painted white, and three towers (circle, square, triangle). Each tower, also constructed of wood, measured 7.62cm in height with a 2.54cm diameter and was painted blue. The series of nine objects, each containing an interior aperture (see Figure 3), were constructed based on all possible combinations of a circle, square, or triangle aperture embedded in a circle, square, or triangle solid shape. Each object's outer solid shape measured 8.89cm, while the interior aperture measured 3.81cm. The objects were constructed of wood and painted yellow.

Children were seated at a small, size-appropriate table and given a pre-test training to demonstrate the target actions. The training board was a pentagonal tower, 10.16cm tall with a 2.54cm diameter, situated on a 13.97cm x 13.97cm x 3.175cm base. There was a corresponding compound object, with both a pentagonal outer surround and inner aperture. The solid surround measured 6.35cm, and the pentagonal aperture was 3.81cm in diameter (see Figure 5). All tasks were recorded using a Canon Vixia HF R600 high-definition video camera set up on a tripod.

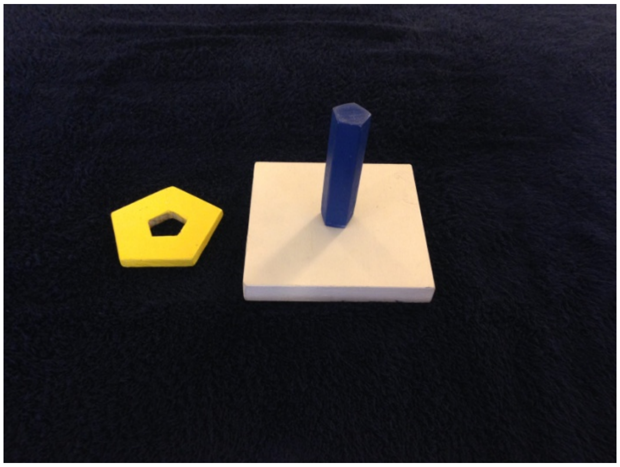
Figure 5. Pentagonal training tower.

Procedure

Prior to each testing, the towers were placed on the boards in a predetermined, randomized order. The board was on the table and concealed with a decorative cloth. The nine objects were also concealed from the child's view and placed on the floor beside the table. Upon entering the room, the child was asked to sit and place their hands on hand-shaped stickers on the table.

Pre-test training. The child was shown the pentagonal tower, and the experimenter demonstrated the corresponding object fitting on the tower and sliding all the way down to the board. The experimenter then told the child the object goes all the way down and asked the child to point to the tower with a prompt of, "Where will this piece go all the way down?" In later trainings, the child was asked to physically make the object fit onto the pentagonal tower as a means of demonstrating the targeted action.

Tower selection condition. In the tower selection condition, the child was shown one object at a time in a randomized order (see Figure 4a). The object was placed in canonical orientation on the middle of the board, aligned with the edge closest to the child, by the experimenter, who then prompted the child by asking where the piece will go all the way down. This procedure was repeated for each of the nine objects.

Perception task. The perceptual task required the child to point to the corresponding tower on which the object would fit. The child was not allowed to pick up the object to ensure the child received no haptic feedback and the task was purely perceptual. This was repeated until the child was presented with each of the nine objects.

Action task. During the action task, the child was instructed to physically place the object on the corresponding tower. The pentagonal training tower was used for children who did not understand the target action required. As in the perception task, the child was shown one object at a time, in a randomized order, until the child had attempted to fit all nine objects on the corresponding tower.

Object selection condition. In the object selection condition, the child was shown three objects at a time with one tower on the board (see Figure 4b). Each of the three towers had three associated trials, all of which were randomized. One trial consisted of the three objects that matched the external shape of the tower (e.g., three external triangles). A second trial consisted of the three objects that had the internal aperture matching the tower (e.g., three internal triangles). A third trial was a mix of incongruent objects (e.g., external square with internal triangular aperture; external triangle with internal circular aperture; external circle with internal square aperture). The experimenter placed the three objects, equally spaced, on the board. All objects were aligned with the edge of the board closest to the child and placed in the canonical orientation. The experimenter prompted the child by asking which piece will go all the way down. This was repeated for each of three towers, resulting in nine total trials.

Perception task. This required the child to point to the object that would fit on the corresponding tower. As with the three tower task, the child was not allowed to pick up the objects. This was to ensure the child received no haptic feedback from handling the objects.

Action task. During the action task, the child was asked to physically fit the object onto the corresponding tower. The pentagonal training tower was used to demonstrate the targeted action for children who did not understand what was being asked. The task was complete after the child completed each of the three trials associated with the three towers.

Data Coding

All trials of the perception and action tasks in both the tower and object selection conditions were examined using the behavioral coding program Datavyu (Version 1.2; Datavyu Team, 2014). The primary variable of interest during coding was success of selection, defined by whether the selection was the correct match. Success was determined based on the initial choice made by the participant. The current study was not focused on measuring children's ability to rotate and adjust the shapes to achieve full fitting on the tower. Instead, shape perception and the relation between the contours of positive and negative space was measured. Therefore, success was coded based on the initial selection (e.g., first contact of the shape to the tower), rather than the ability of the child to manipulate the shapes to achieve fully fitting the shape onto the tower (Örnkloo & von Hofsten, 2009). Additional variables of interest, seen in Table 2, were based on the properties of the objects selected in each trial. Coding was done by two independent raters. Inter-rater reliability, based on dual coding of 20 percent of the total sample, was high (Cohen's Kappa = .974).

Table 2

Variables of Interest for Behavioral Coding

Success	Variable of Interest	Description
Match	Congruency	Whether the pieces presented and/or selected had congruent inner and outer shapes (e.g., triangle aperture, triangle outer shape) or incongruent inner and outer shapes (e.g., triangle aperture, circle outer shape)
Mismatch	Type of Error	Whether the incorrect selection was consistent with the compound object's outer shape (e.g., piece is inner triangle, outer circle; child selects circle) or was made without regard for the information available (e.g., piece is inner triangle, outer circle; child selects square)

Note. Inner aperture shape, outer surround shape, and tower shape was recorded for each trial, regardless of success of selection.

Results

Data were analyzed using Generalized Estimating Equations (GEE), an analysis that performs repeated measures multiple regressions, using age as a continuous variable. The use of GEE accounts for correlated, non-normally distributed data, because the distribution shape and correlation matrix can be specified before analysis (Liang & Zeger, 1986). An exchangeable correlation matrix with a binary logistic distribution was used, because trials were correlated by participant, and the dependent variable (success) was coded as either correct or incorrect. The use of GEE also allowed for the accommodation of missing data from participants who were not able to complete all 36 trials. Out of the possible 2,304 trials, participants completed over 96 percent (2,216 completed). After presenting results from preliminary analyses, we will examine success and then examine the influence of the relation between shapes on children's actions.

Preliminary Analyses

Preliminary GEE modeling showed that successful fitting was not influenced by testing location (preschools vs. University lab, p = .432) or the order in which the perception and action tasks were presented (p = .667). Additionally, participant sex did not significantly influence success (p = .36), the number of missing trials (p = .094), or trial duration (p = .989). Therefore, data were collapsed across these variables in subsequent analyses.

Next, we examined the influence of task (perception task vs. action task) on performance. Children's successful fitting was not affected by task (p = .332). Because of the theoretical interest in potential differences in the perception vs. action versions of the task, further analyses relating to this factor were conducted to examine any potential differences when isolating performance in each condition (object selection vs. tower selection). We isolated trials from the object selection condition and found that task (perception vs. action) did not significantly influence successful matching (p = .798). We then isolated trials from the tower selection condition and again found that task (perception vs. action) was not a significant predictor of successful matching (p = .186). Based on these findings, data were collapsed across perception and action tasks as well in subsequent analyses**.**

Success

We first examined developmental differences in success by regressing successful selections onto age in GEE. Object selection trials in which the three compound stimuli contained inner apertures matching the single tower were removed from the analysis, because as long as an object was selected by the participant on such trials, it would successfully fit onto the tower. As expected, success increased with age (see Figure 6). GEE modeling confirmed a significant effect of age (Wald χ^2 = 32.838, p < .001), suggesting that the ability to match negative space to positive space improves during the toddler period. Additionally, we computed confidence bands to determine at which point successful matching significantly exceeded chance level responding (33%) and found that this occurs around the 23rd month, as seen in Figure 6.

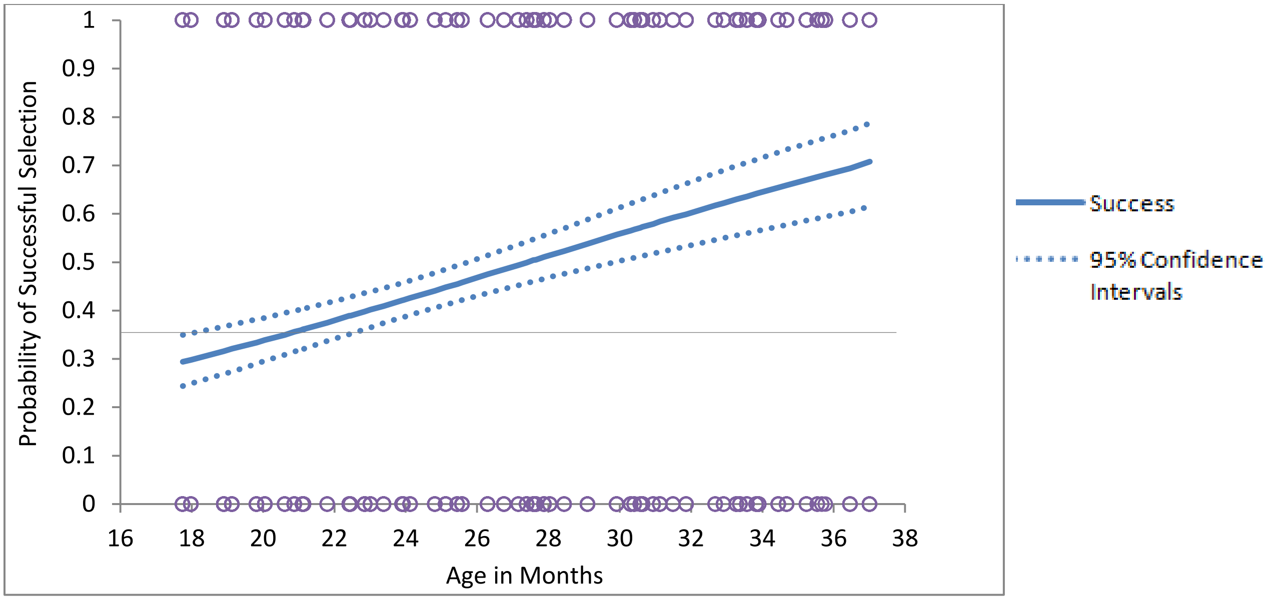

Figure 6. Main effect of age. Raw data showing success of selections (1 = correct; 0 = incorrect) are indicated by the purple circles.

Next, at the individual participant level, we examined successful matching by obtaining the proportion of correct responses for each participant. Overall, the total number of successful trials across age was 1,297. The raw data (see Figure 7) generally show that the proportion of correct responses, ranging from .17 to 1.0, begins to increase near 26 months of age.

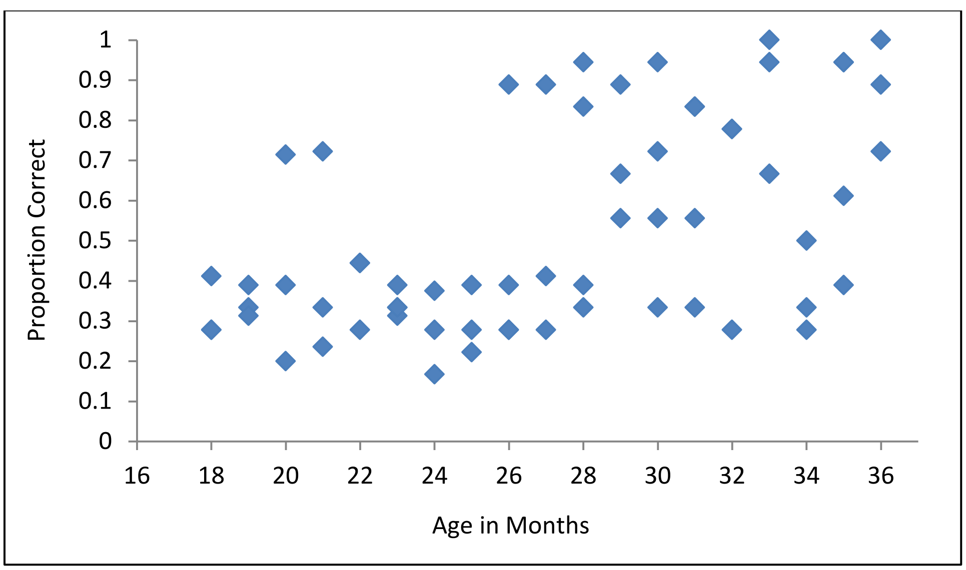

Figure 7. Raw data showing the proportion of correct trials for individual participants.

To examine how these proportions change with age and compare success to that of chance responding (33%), the participants were split into three age groups: 18- to 24-month-olds (*n* = 23, *M* = 21.24 months, *SD* = 0.016), 25- to 30-month-olds (*n* = 21, *M* = 27.93 months, *SD* = 0.036), and 31- to 36-month-olds (*n* = 20, *M* = 33.74 months, *SD* = 0.041). The age ranges were chosen based on past fitting literature, which suggests a developmental progression consistent with these ranges (Jung, et al., 2015; Örnkloo & von Hofsten, 2007; Shutts, et al., 2009). Between 18 and 24 months of age, children begin to successfully match objects to apertures. By 30 months, matching improves and becomes more consistent, and by the end of the 3rd year, children perfect this ability.

Successful responding within each of these age groups was compared to 33% chance using Fisher's exact test (see Figure 8). The 18- to 24-month-old children were successful on 36% of trials, which was not significantly different than chance ($p = .262$). The 25- to 30-month- old children were successful on 55% of trials ($p < .01$), and the 31- to 36-month-old children were successful on 68% of trials ($p < .001$).

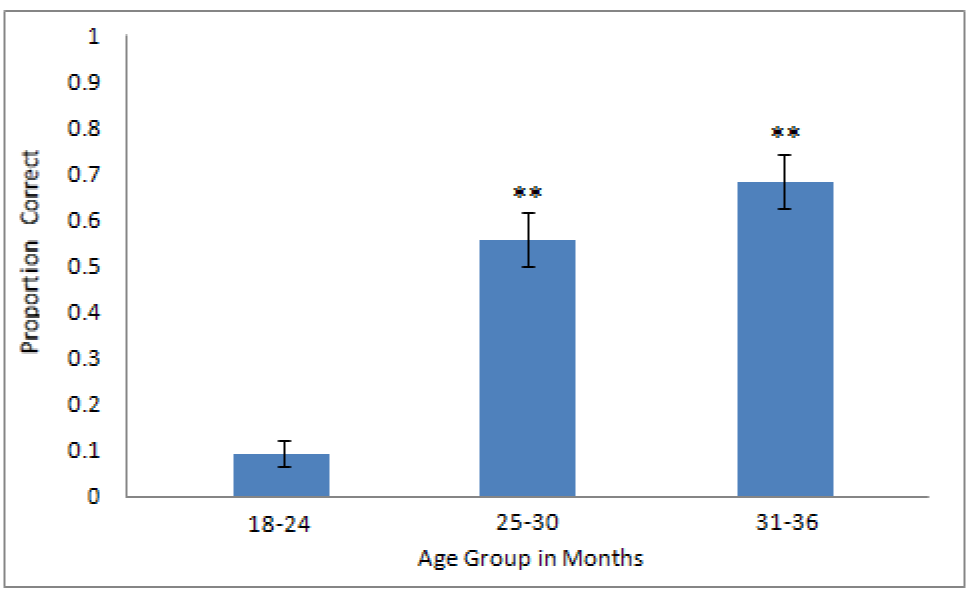

Figure 8. Proportion of correct responses for individual participants within each age group.

Then, using the binomial distribution, we compared each participant's correct responses to that of chance responding (see Figure 9) to determine how many individual participants in each age group were successful at a rate exceeding chance. Of the 23 participants between 18 and 24 months, only two (9%) performed above chance. Of the 21 participants between 25 and 30 months, 10 (48%) performed above chance. Of the 20 participants between 31 and 36 months, 14 (70%) performed above chance. Collectively, these individual-level analyses further illustrate that children's successful matching increases with age as well as indicate the point at which successful matching begins to exceed chance levels.

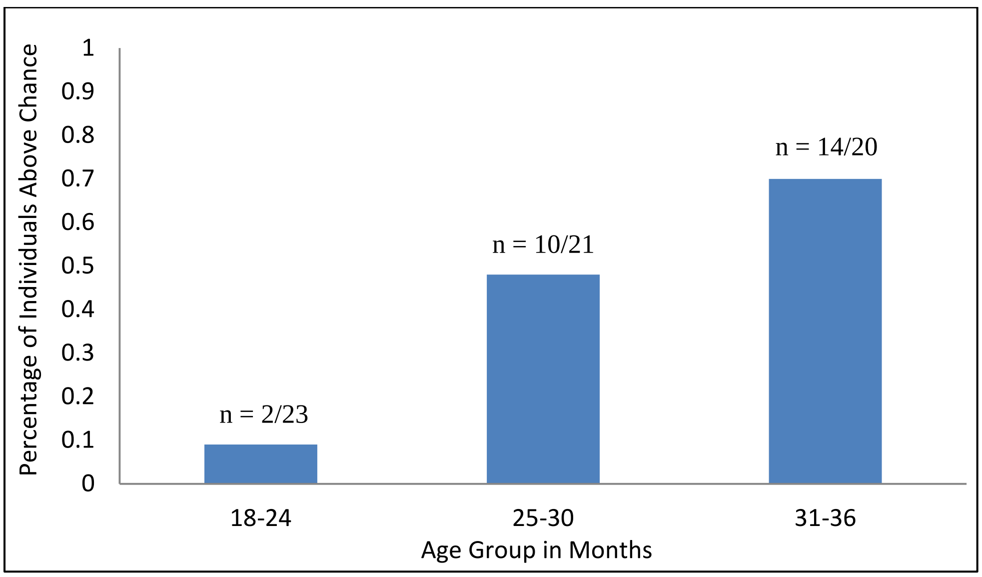

Figure 9. Participants significantly above chance in each age group.

Object selection vs. tower selection success. We next explored whether successful fitting was influenced by condition (object vs tower selection). We regressed successful selections onto age and condition in GEE, again removing object selection trials in which the three compound stimuli contained inner apertures matching the single tower. We found that children's performance was affected jointly by age and condition. Although there was no main effect of condition, a significant Age x Condition interaction was found (Wald $\chi^2 = 4.157$, $p = .041$), indicating that choosing amongst the towers (tower condition) becomes easier for children at earlier ages than choosing amongst the compound stimuli (object condition). Further, choosing amongst objects continues to be more difficult for children than choosing amongst towers, even at older ages. As illustrated by the confidence bands in Figure 10b, children's success when selecting amongst the towers begins to exceed chance responding (33%) near the 23rd month. In contrast, when selecting amongst the compound stimuli, children's success begins to exceed chance responding closer to the 25th month (Figure 10c).

Collectively, the results suggest that children's ability to match negative space to positive space improves with age. Additionally, choosing amongst the compound stimuli may be more difficult than choosing amongst the towers. We next explore why choosing among the compound stimuli may be challenging for young children by considering how the internal and external shapes of the compound stimuli influence responding.

Object Shape and Congruency

To explore the ways in which the relation between the inner aperture and solid surround shapes affected performance, we examined the tower and object conditions separately and focused on the influence of congruency. We defined congruency as the relation between the inner aperture shape and the shape of the object's solid surround. Congruent compound objects have matching apertures and surrounding shapes (e.g., circle aperture embedded in circular solid surround), whereas incongruent compound objects (e.g., circle aperture embedded in square solid surround) have aperture and surrounding shapes that are different from one another.

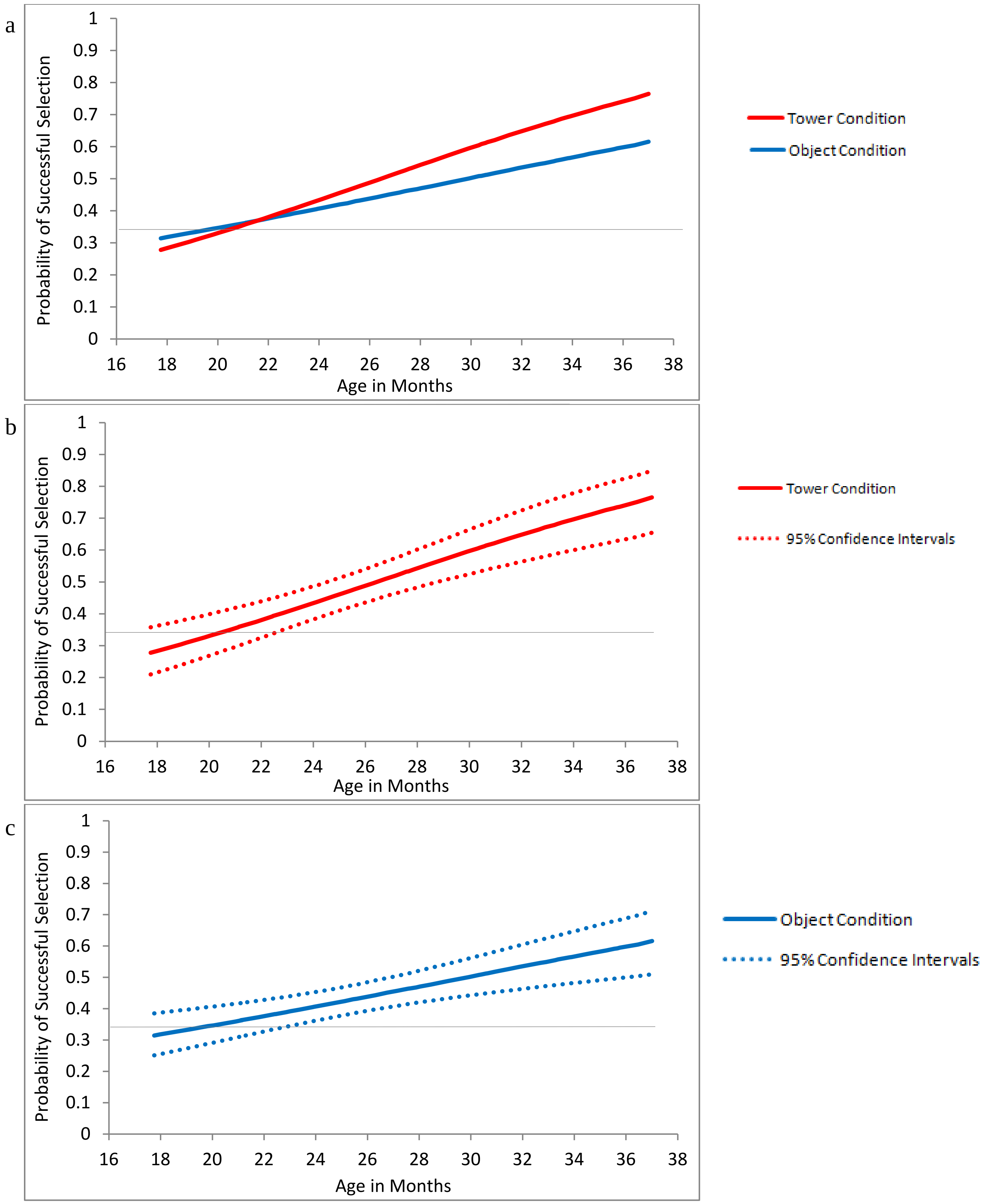

Figure 10. (a) Age x Condition interaction, (b) shown with 95% confidence bands for the tower and (c) object selection conditions.

Tower selection condition. Recall that in the tower condition, each of the nine compound stimuli are presented one at a time, and children select the tower (out of three possibilities) on which the stimulus will fit. We consider children's rate of success with each of the nine compound objects, and then examine developmental differences associated with congruency.

Success rates. We first obtained the rates of successful matching for each of the nine compound stimuli in the tower condition (see Figure 11). Overall, these rates indicate that children were most successful when matching the congruent objects, which we confirmed using pair-wise comparisons. Children's success with the congruent circle was significantly higher than for the incongruent objects containing circular apertures embedded in a square ($p < .001$) and a triangle ($p < .001$). Similarly, children were significantly more successful with the congruent triangle than with the incongruent triangle apertures embedded in a circle ($p = .015$) and a square ($p = .008$), while success with the congruent square was significantly higher than success with the square apertures embedded in a circle ($p < .001$) and a triangle ($p < .001$). Collectively, these findings suggest that children can more easily select the correct tower when presented with objects that have matching inner aperture and solid surround shapes.

The success rates also indicate that on trials in which the compound objects are incongruent, the square shaped apertures are the most difficult for children to match to the tower. As seen in Figure 11, when presented with the two incongruent objects with square apertures, children are performing only around chance levels. We then compared children's performance matching incongruent objects with square apertures to performance matching incongruent objects with circle and triangle apertures, again using pair-wise comparisons. The results confirmed that performance with incongruent square apertures was significantly below performance with incongruent objects containing circle ($p < .001$) and triangle ($p = .005$) apertures.

Generally, the results suggest that congruent compound shapes are easier for children to match than incongruent ones. Additionally, when children are tasked with fitting incongruent compound objects onto other objects, square-shaped apertures may be more difficult to process than circular and triangular apertures.

Object

Success	75.6 ***	62.1 ***	59.88 ***	54.5 **	50.8 **	50.0 *	50.0 *	37.4	36.6

Note. Success rates were compared to chance responding of 33%. * $p < .05$. ** $p < .01$. *** $p < .001$

Figure 11. Success rates for individual objects in the tower selection condition.

Age-related effects associated with congruency. We next explored developmental effects associated with the congruency (inner and outer shapes) of the compound objects in the tower selection condition. Using GEE modeling, we regressed success onto age and object congruency. As expected, a significant main effect of age (Wald $\chi^2 = 28.57$, $p < .001$) was found. Additionally, we found a significant Age x Congruency interaction (Wald $\chi^2 = 8.744$, $p = .003$). Between 18 and 36 months, children become successful earlier with congruent compound objects compared to incongruent ones (see Figure 12). Additionally, as indicated by the confidence bands, children's success with congruent objects exceeds chance responding (33%) around the 22 month, while success with the incongruent objects exceeds chance responding around the 26 month. Further, even by the end of 36 months, children are still experiencing more difficulty when matching an incongruent compared to a congruent compound object to a tower.

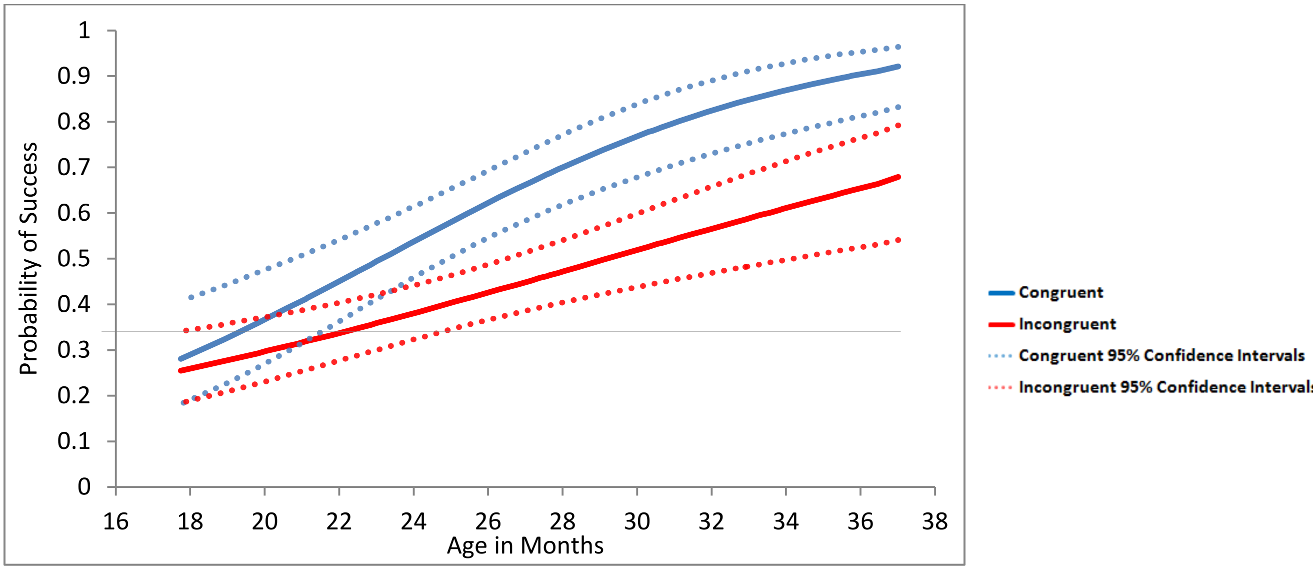

Figure 12. Age x Congruency interaction. Around 24-months olds, the probability of success is significantly different based on the congruency of the object presented.

Object selection condition. We next focused on children's performance in the object selection condition. Recall that in this condition, three compound objects are presented with a single tower. Children select which of the three stimuli will fit on the tower. We first consider the frequency with which congruent objects were selected compared to incongruent objects. Next, we examine developmental differences in object selection associated with congruency.

Selection frequency. We first examined trials in which the inner aperture matches were presented in the object selection condition to look at how the solid surround of the compound object influenced children's choices. As noted, inner aperture match trials refer to trials in which all three compound object choices contained an inner aperture shape that matched the single tower. Thus on the these trials, children were correct regardless of the choice they made, enabling us to examine directly whether the congruency of the inner and outer shapes influenced selection.

We examined how often each compound object was selected on these trials (see Figure 13). Overall, congruency boosted selection with two of the shapes: the congruent circle and congruent triangle. Using the binomial distribution and Fisher's exact test, we found that when the objects with circular apertures were presented, the congruent circle was selected significantly above 33% chance ($p < .001$) and significantly more often than the other two objects ($p < .0001$). Similarly, when the objects with triangular apertures were presented, the congruent triangle was selected significantly above 33% chance ($p < .01$) and significantly more often than the other two objects ($p < .01$).

In contrast, when the objects with square apertures were presented, the selection rates of the objects did not significantly differ from chance or each other (ps > .05). These results are consistent with the prior ones suggesting that children may have difficulty processing the square shape in relation to other shapes.

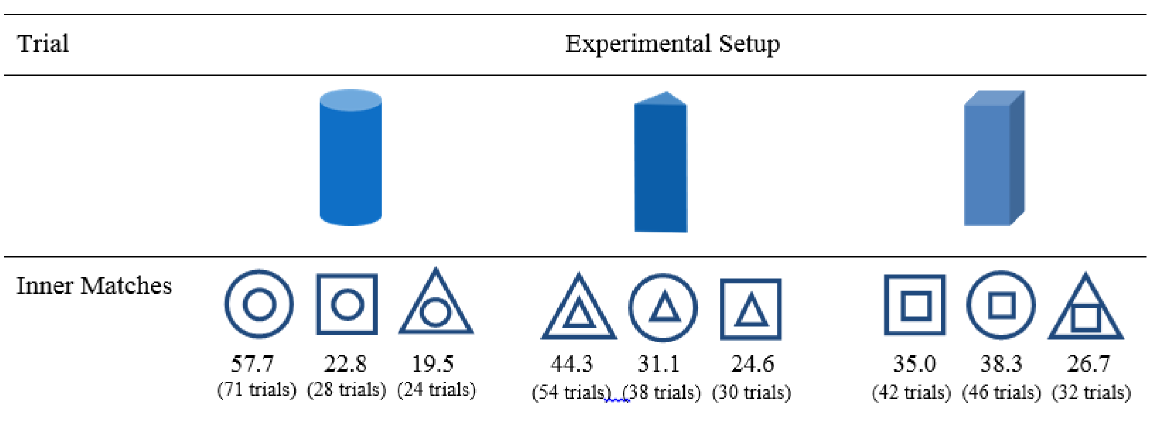

Figure 13. Frequency of selection on trials in which the objects with inner aperture shapes matching the tower are presented in the object selection condition.

Age-related effects associated with congruency. We next explored developmental effects associated with the congruency (inner and outer shapes) of the compound objects in the object selection condition. We regressed the congruency of the object selected onto age in GEE, again only including trials in which all the inner aperture shapes match the tower. We found a significant effect of age (Wald $\chi^2 = 19.251$, $p < .001$), such that younger children selected incongruent compound objects more frequently, while older children selected congruent compound objects more frequently (see Figure 14). Congruent selections begin to exceed chance level responding (33%) around 27 months of age, as indicated by the confidence bands.

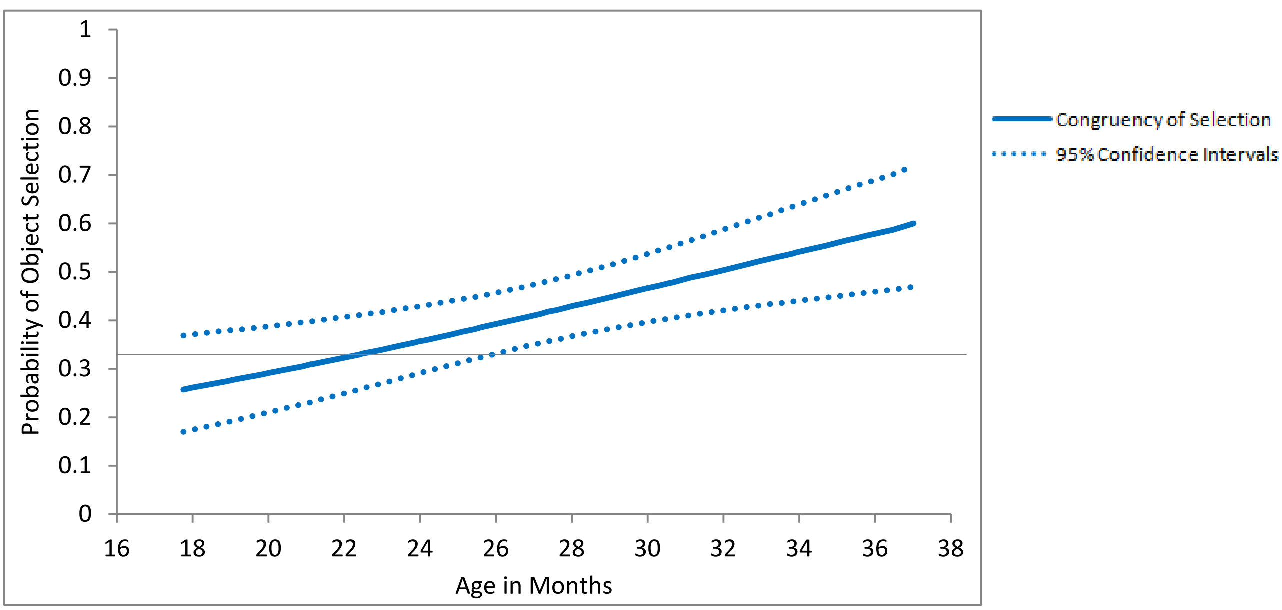

Figure 14. Effect of age on congruency of object selected. Younger children more frequently select incongruent objects (0), while older children select congruent objects (1) more frequently.

Collectively, the results from the object selection as well as the tower conditions suggest that congruency influences success. Additionally, on trials in which all three compound objects contained inner aperture matches, congruency influenced which object children selected.

Unsuccessful selections: Type of error. Finally, to investigate the influence of the relation between the compound object's inner and outer shapes, we examined the types of errors children made on incongruent trials. Our primary interest was whether unsuccessful selections were based on the outer shape of the compound object or on a different shape (neither the inner nor outer shape of the compound stimuli).

***Tower selection condition*.** We first examined the type of error made in the tower selection condition. Again, recall that in the tower condition, each of the nine compound stimuli are presented one at a time, and children select the tower (out of three possibilities) on which the stimulus will fit. Type of error in this condition was based on the relation between the compound object and tower such that children could select a tower that matched the outer shape of the compound object or a tower that matched neither the inner nor outer shape of the compound object. Errors involving the three congruent stimuli (e.g., circle within a circle) were removed from the model, as the inner and outer shapes were identical. The type of error (outer shape of the compound object vs. neither the inner nor outer shape) made was regressed onto age using GEE. We found a significant effect of age (Wald $\chi^2 = 7.287$, $p = .007$), such that younger children more frequently made incorrect selections that did not correspond to either the inner or outer shape of the compound object. In contrast, older children more frequently made incorrect selections that were based on the solid surround shape of the compound stimulus. It is important to note, however, that even at the youngest ages, children choose the outer shape of the compound object at rates exceeding chance responding (50%), as indicated by the confidence bands in Figure 15.

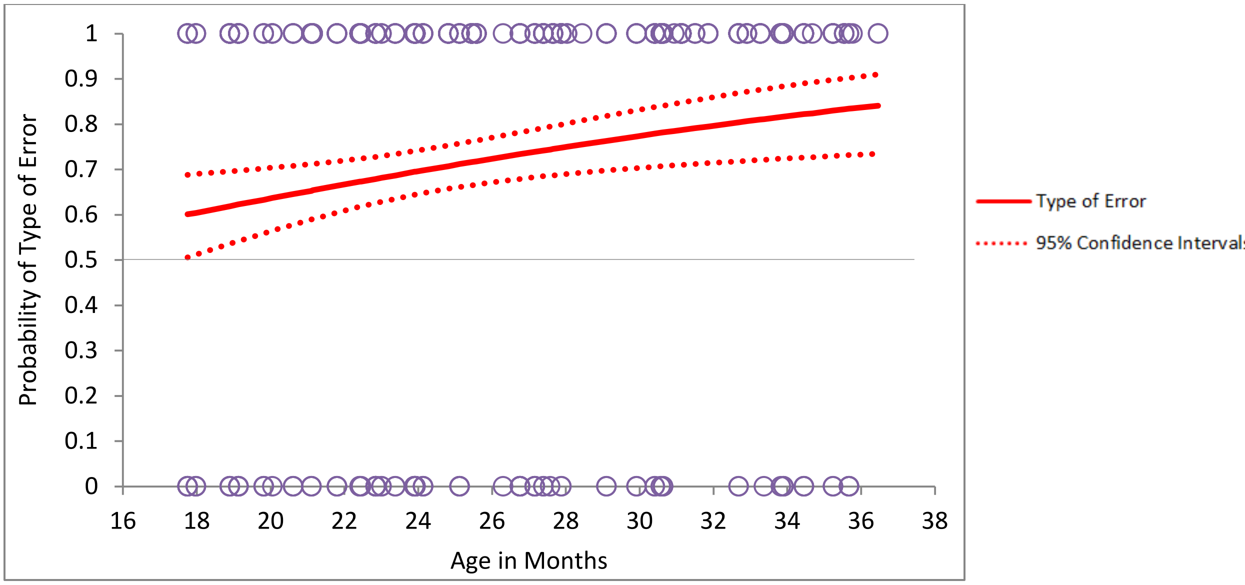

Figure 15. Effect of age on type of error. Raw data showing the type of Error (0 = neither; 1 = outer shape) is indicated by the purple circles.

Object selection condition. We next examined the type of error made in unsuccessful selections in the object selection condition. Recall that in this condition, three compound objects are presented with a single tower, and children select which of the three stimuli will fit on the tower. We included only the trials in which three incongruent stimuli were presented and regressed the type of error made onto age in GEE. Trials in which all three stimuli had inner apertures matching the tower were removed, because as long as a selection was made, it was correct. Trials in which all three stimuli had solid surround shapes matching the tower were also removed, because both possible errors would involve the same outer shape as the tower. Results revealed again a significant effect of age (Wald $\chi^2 = 6.019$, $p = .014$), such that younger children more frequently made incorrect selections that did not correspond to either the inner or outer shape of the compound object. In contrast, older children more frequently made incorrect selections consistent with the solid surround shape of the compound stimulus (see Figure 16). Additionally, the analyses revealed that the type of error made (outer shape of the compound object vs. neither the inner nor outer shape) did not become significantly different from chance until around 29 months, as indicated by the confidence bands in Figure 16.

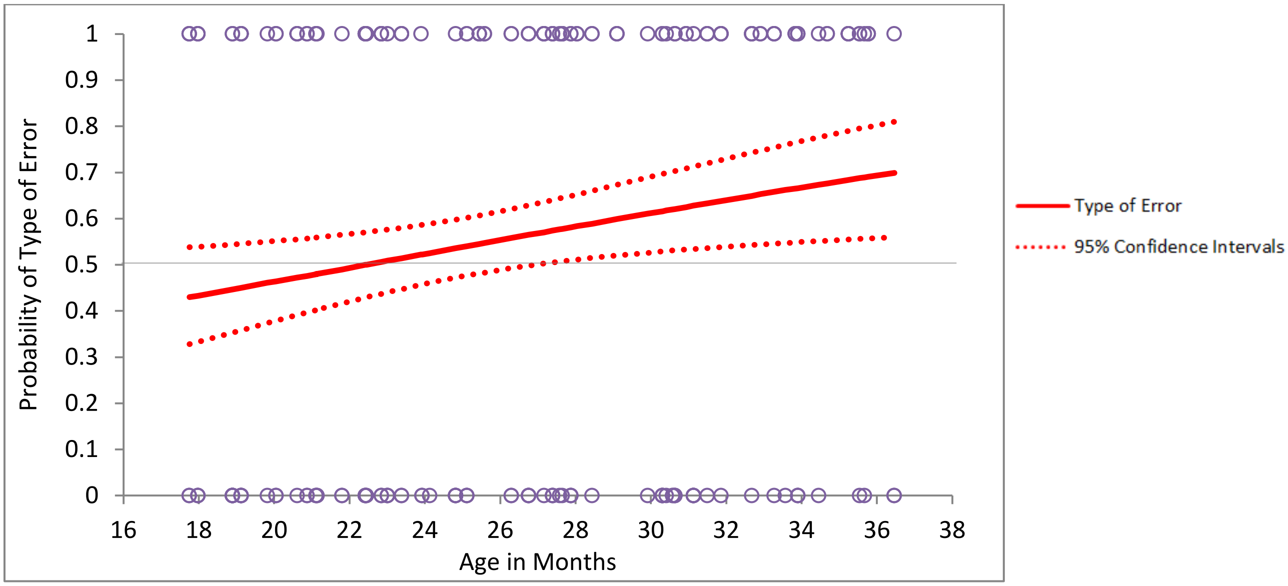

Figure 16. Effect of age on type of error. Raw data showing the type of error (0 = neither; 1 = outer shape) is indicated by the purple circles.

Finally, we examined the type of errors made (outer shape vs. neither shape) in unsuccessful selections among individual participants. One participant made no errors and was therefore excluded from these analyses. The raw data, comprised of responses from the remaining 63 participants, show at the individual child level the proportion of types of errors, ranging from 0 to 1, in which a child selected the outer shape of the compound object (see Figure 17). Overall, across age, children made a total of 283 errors based on the outer shape of the compound object and 227 errors based on neither.

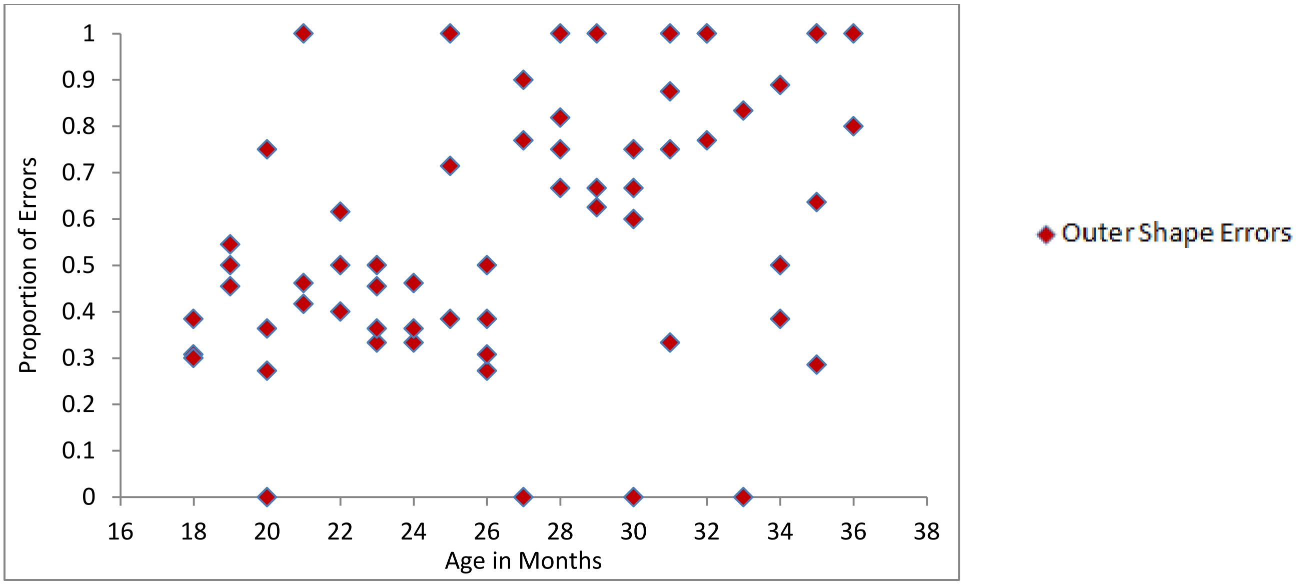

Figure 17. Raw data showing the proportion of outer shape errors made in unsuccessful selections.

To examine how these proportions change across development and compare selections to that of chance responding (50%), the participants were split into the same three age groups used in prior analyses, and the errors made in unsuccessful selections were compared to chance using Fisher's exact test (see Figure 18). The 18- to 24-month-old children selected based on the outer shape on 44% of trials, which was not significantly different than chance ($p > .05$). The 25- to 30-month-old children selected based on the outer shape on 61% of trials ($p = .02$). The 31- to 36-month-old children selected based on the outer shape on 72% of trials ($p < .01$).

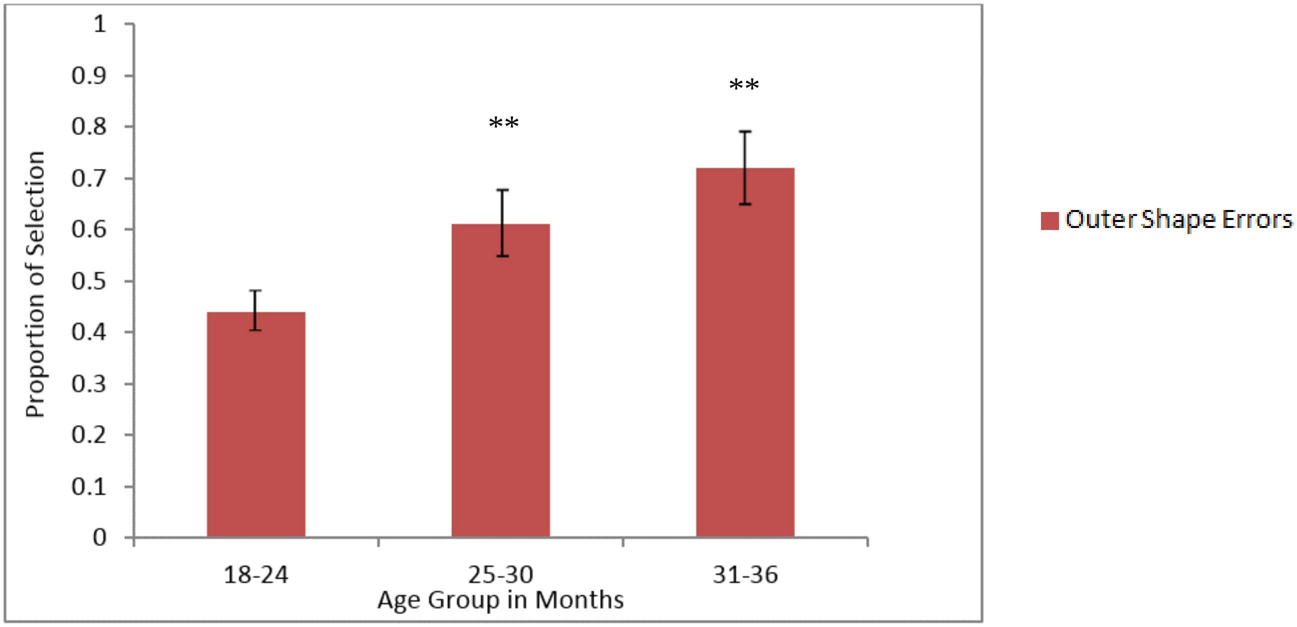

Figure 18. Proportion of outer shape errors made by individuals within each age group. Responses significantly differed from chance among the 25- to 30-month-olds and among the 31- to 36-month-olds.

Using the binomial distribution, we then compared the types of errors made by each participant to that of chance responding (50%) in order to determine how many individual participants in each age group made selections based on the outer shape at a rate exceeding chance (see Figure 19). Of the 23 participants between 18 and 24 months, only four (17%) chose the outer shape at a rate exceeding chance. Of the 21 participants between 25 and 30 months, seven (33%) chose based on the outer shape at a rate exceeding chance. Eleven of the 19 (63%) participants between 31 and 36 months selected based on the outer shape at a rate above chance.

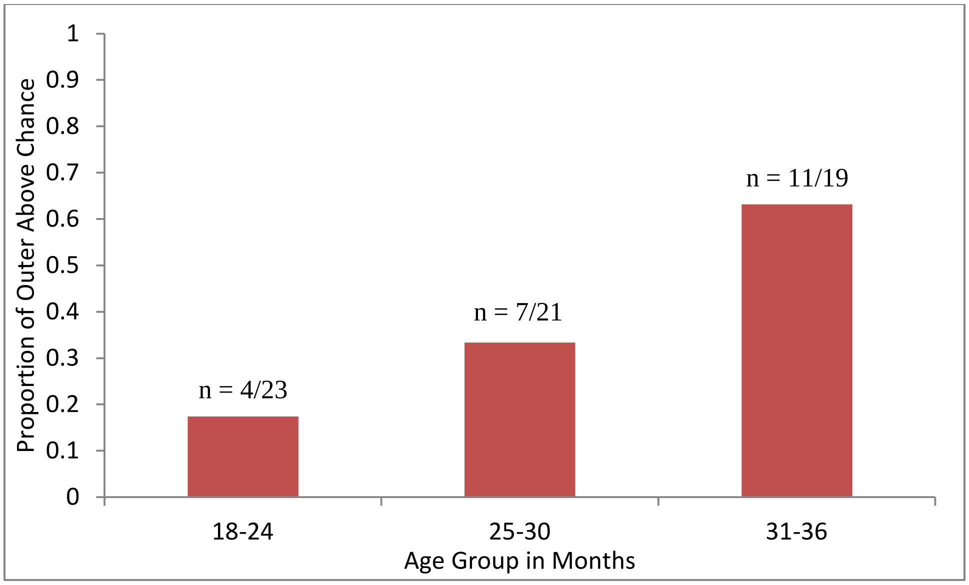

Figure 19. Participants who made errors consistent with the outer shape of the solid surround at a rate exceeding chance.

The results indicate that in the object selection condition, younger children's unsuccessful matching attempts are based on neither shape represented by the compound stimulus. With age, these mistakes become based on the solid surround of the compound stimulus. In contrast, in the tower selection condition, children's mistakes across age are most often based on the solid surround shape of the compound object. Additionally, the frequency with which children's errors are based on neither shape decreases with age, which is consistent with findings from the object selection condition. Overall, the types of errors results suggest that with increasing age, children's mistakes become more often based on the outer shape of the solid surround.

Discussion

With the current study, we provide new information about the development of preschool children's understanding of spatial relations. Fitting objects together is an adaptive ability that involves shape recognition, and this ability is related to early mathematical thinking and later academic outcomes in STEM areas (Grissmer et al., 2013; Newcombe, 2010; Verdine et al., 2014; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017). However, our understanding of the ways in which children relate shapes in fitting tasks has been limited in two important ways.

First, much of the existing research is on individual object recognition (Pereira et al., 2010; Slater et al., 1983; Smith et al., 2014; Yonas & Granrud, 1985) and recognizing individual shapes from incomplete information (Bertamini & Croucher, 2003; Tarr, 1995). Rather than focusing on individual object and shape recognition, the current study examined the process of relating shapes to shapes.

Second, previous fitting research has traditionally been on fitting objects into apertures (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Shutts et al., 2009). This type of fitting requires children to relate positive space to negative space. The current study instead focused on fitting negative space to positive space by asking children to fit the apertures of compound objects (shapes within shapes) onto towers. Because the aperture was necessarily embedded in a solid surround, we also considered how the relation between negative and positive space (i.e., shapes of the aperture and solid surround) influenced fitting. Although the influence of shapes within shapes has been implicit in much of the past work, it has never, to our knowledge, been explicitly addressed.

To address these larger issues, we presented 18- to- 36-month-old children with two conditions of a fitting task: an object selection and a tower selection condition. In the object selection condition, children were presented three differently shaped compound objects (apertures embedded in solid surrounds) and selected one of these to fit onto a single tower. In the tower selection condition, the same children were shown a single compound object and selected amongst three differently shaped towers to accomplish fitting.

Within each the object selection and tower selection conditions, children completed two tasks: a perception only and an action task. Recall that half of trials required children to indicate their selection by pointing to either the object or tower (perception only task). The other trials required children to physically fit the object to the tower (action task). No differences in successful fitting were found between the perception and action tasks. Past neural work (Dilks et al., 2008; Milner & Goodale, 1995) has suggested that relating objects to other object involves two distinct neural systems: the ventral stream (vision for perception) and the dorsal stream (vision for action). Research has suggested the two streams develop at different rates before beginning to work in tandem around 24 months (Street et al., 2011). Although the current study did not examine children younger than 18 months, we found no significant Age x Task (perception vs. action) interaction (p = .305) across the entire age range, suggesting that differences in success were not due to task. Based on the lack of differences between the perception and action tasks, we found no evidence to suggest that the two visual streams develop at different rates in the present fitting study. To further our understanding of the development of the two visual streams, future fitting studies might investigate perception and action differences in children younger than 18 months.

The current study, therefore, examined fitting negative space (aperture of the compound shape) to positive space (tower). The main findings suggest that the ability to fit negative space to positive space develops later than the ability to fit positive space to negative space, and this ability differs by condition (object selection vs. tower selection). Additionally, we found that the action of fitting the aperture of a compound object onto another object is influenced by the outer shape of the compound object, as well as the shape of the inner aperture in relation to the outer shape of the compound object.

Success

Not surprisingly, children became more successful matching the compound stimuli to the towers with age. Successful responding across the object selection and tower selection conditions began to exceed chance responding around 23 months of age. Additionally, individual level analyses indicated that there is a sharp increase in successful responding around 26 months of age. Past fitting work examining fitting positive space to negative space has found a similar increase in successful responding, but this improvement occurs between 20 and 24 months (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Shutts et al., 2009). The increase in successful responding at 26 months in the current study occurs at an older age than indicated by past research. By splitting participants into three age groups, we were able to examine these differences more closely.

In the current study, only 9% of participants in the youngest age group (18 to 24 months) performed significantly above chance. Of the children in the middle age group (24 to 30 months), 55% performed above chance, while 68% of children in the oldest age group (30 to 36 months) exceeded chance levels. When comparing these results to those from Shutts and colleagues (2009) in which children matched positive to negative space, there is a marked difference in performance. In that study, 70% of children were performing significantly above chance by 24 months, and by 30 months, this increased to 90%. The differences between findings from past work and the current study suggest that matching negative space to positive space is more challenging for children than the reverse.

The difficulties children appear to have with understanding negative space can also be seen when considering our findings comparing the two conditions (object selection vs. tower selection). We found that successful responding differs by condition, such that choosing amongst objects (object selection condition) was harder for children than choosing amongst towers (tower selection condition). Children began performing above chance levels about two months earlier in the tower selection condition. Even at the oldest ages, choosing amongst objects was still harder for children than choosing amongst towers. When choosing amongst towers, children are selecting from positive space exemplars. When choosing amongst objects, however, children are selecting the aperture of the compound stimuli, which involves discriminating amongst different contours of negative space. The difference in performance between the two conditions was also found when examining other factors predicting success (i.e., congruency) and the types of errors children made on incorrect selections. This consistent pattern further highlights the idea that children have more difficulty acting on negative than positive space.

Collectively, our findings regarding successful selections indicate that although children’s ability to match negative to positive space improves with age, this ability appears to be more difficult than the ability to match positive to negative space. We consider two possible explanations for this pattern of findings. First, the shape of the compound objects’ solid surrounds may play a role in the difficulty children experience with negative space. Another possible explanation is that negative space is necessarily embedded within positive space, which can lead to conflicting shape information between the negative space of the aperture and the positive space of the solid surround. These two possibilities are explored in turn.

Influence of Shape

As proposed by Piaget and Inhelder (1948/1956), preschool-aged children were thought to be capable of only considering topological relations within space (i.e., adjacency, enclosure) and unable to focus on Euclidean features of shapes (i.e., distance, angular, metric information). Yet in the current study, children are making distinctions amongst shapes, at ages when Piaget and Inhelder (1948/1956) argued they could only consider topological information. Our results demonstrate that children between 18-and-36-months-old are sensitive to angular information during object fitting: Even at the youngest ages, children successfully fit some apertures onto objects, which requires them to consider Euclidean features.

Additionally, it appears that children distinguish amongst shapes more easily when the objects contain circles compared to objects with squares and triangles. Overall, children were most successful when fitting the circular compound objects. Further, when children were asked to choose amongst three objects in the object selection condition, the circular shapes were selected more frequently than the square and triangle shapes.

Children's more frequent selection of circles in the object selection condition could be explained by findings from work with adults, which suggest that people tend to prefer curved shapes over angular shapes (Bar & Neta, 2006; Bertamini, Palumbo, Gheorghes, & Galatsidas, 2016; Jadava, Hines, & Golombeok, 2010; Silvia & Barona, 2009). One possible reason for this adult preference is that circles are seen as more aesthetically pleasing than angular or elongated shapes (Albertazzi, Canal, Dadam, & Micciolo, 2014) and are considered more organic and in consonance with nature (Gómez-Puerto, Munar, & Nadal, 2016) than angular forms, which are seen as more geometric and mathematical (Rovetto, 2011). The preference for curvilinear shapes over angular shapes may also occur because angular shapes are seen as more threatening (Bar & Neta, 2006; Bertamini et al., 2016), particularly with regards to facial features. While curvilinear shapes are consistent with happy expressions (e.g., rounded cheeks in a smile), angular forms are consistent with angry expressions (e.g., clenched jaw, downward angled eyebrows), making curvilinear shapes less threatening and more appealing (Aronoff, Woike, & Hyman, 1992).

Alternatively, children's more frequent selection of (object selection condition) and success with (tower selection condition) circular shapes compared to squares and triangles might occur because circles are seen as more flexible and changeable, while squares and triangles are viewed as more rigid and fixed. For example, children's daily experiences with clothing could provide information that circular shapes are expandable.

The arm and neck holes of shirts are usually elastic and thus more flexible. Similarly, the pants worn by preschool-aged children expand once they insert their bodies. The perceived changeable nature of circular shapes would also explain why children selected the circular objects more frequently in the object selection condition.

Selective Attention

Negative space may also be more challenging for children to act on because it embedded within positive space. When the aperture and solid surround of a compound object are shaped differently (e.g., circular aperture embedded in a square), it results in conflicting spatial information between the negative space of the aperture and the positive space of the solid surround. The ability to match the aperture of the compound object to the tower may thus require children to selectively attend to the inner aperture shape of the compound object. Children must use only the relevant information from the compound stimuli (the shape of the aperture) while inhibiting the irrelevant information (the shape of the solid surround). Past work has suggested that younger preschool children have difficulty ignoring irrelevant information and thus are unable to respond to multi-dimensional stimuli based on a single dimension (Doebel & Zelazo, 2015; Frye, Zelazo, & Palfai, 1995; Müller, Zelazo, Hood, Leone, & Rohrer, 2004; Zelazo, Frye, & Rapus, 1996). Additionally, younger preschool children are also more likely to process the compound object holistically but with age become able to understand and selectively attend to a single dimension of the compound stimulus (Hanania & Smith, 2010). This shift in attention is consistent with the age-related effects found in the current study.

The most widely used measure of selective attention in young children is the

Dimensional Change Card Sort (DCCS; Frye et al., 1995; Zelazo et al., 1996), a task in which children are shown pictures of objects that differ on two dimensions (e.g., shape, color). Children are asked to first sort the pictures by one dimension before switching to sort by the second dimension, which requires children to inhibit responses to the now irrelevant stimulus information. At age 3, children continue to sort by the first dimension, but by the age of 5, are generally able to switch (Doebel & Zelazo, 2015). The difficulty 3-year-old children have with switching may be because the original dimension is most salient, and switching attention to a different, less salient dimension is too demanding for children of this age (Doebel & Zelazo, 2015). Related to the current study, perhaps the solid surround shape is more salient for the younger children, which could explain why they have difficulty attending to the inner aperture shape.

To explore this possibility, we examined children's unsuccessful selections. Past work with infants has shown that when a two-dimensional shape is bounded within another shape (i.e., picture of a triangle within a circle), 2-month-old infants fixate only the surrounding shape and are unable to discriminate between two figures with the same outer shape (Bushnell, 1979; Milewski, 1976). This influence of a shape bounded by another shape, known as the externality effect (Bushnell, 1979), was found in the current study. Our results indicate that as children develop, their unsuccessful attempts were most often based on the outer shape of the solid surround in both the tower selection and object selection conditions. These findings suggest that younger children are confused by the different shapes of the compound object and make selections at random. In contrast, older children may have difficulty inhibiting the influence of the more salient solid surround shape.

Enhancing salience. How might attention to the inner aperture shape be promoted? Some research has examined ways to promote attention to the less salient dimension through spatial separation and changes in salience. For example, some variations of the DCCS have shown that spatially separating the two dimensions (e.g., physically separating the two dimensions on a single card) increases 3-year- olds' ability to switch (Kloo & Perner, 2005; Zelazo et al., 2013). Doebel and Zelazo (2015) suggest this is because children have difficulty recognizing that a single object can be described in different ways from different perspectives. In other words, by spatially separating the stimuli, children did not have to account for multiple perspectives of a single object, and therefore did not have to inhibit responses to the first dimension. This explanation may be particularly relevant when considering the current study. Perhaps younger children were only able to focus on a single dimension of the compound stimuli (the outer shapes) and did not fully understand that the compound stimuli could also be described in terms of the internal aperture shapes.

Changes in salience can also influence selective attention. For example, increasing the salience of the second dimension has been shown to improve switching behaviors in the DCCS with 3-year-old children (Zelazo et al., 2013). Similar findings regarding saliency have also been demonstrated in work outside of variations of the DCCS. Bushnell (1979) examined the effects of increasing the saliency of an internal shape bounded by another shape with infants. When the internal shape was made more salient (e.g., oscillating, flashing created by obscuring and revealing internal element), discrimination of the bounded shape became possible. This suggests that the demands of processing a shape within a shape can be eased by increasing salience. When the internal shape is made more salient, changes to that internal form become accessible.

In sum, past research has demonstrated that enhancing salience can promote children's selective attention, which can aid children's ability to match incongruent objects. In the present study, incongruent compound objects require children to selectively attend to the shape of the internal aperture while inhibiting the influence of the solid surround shape; enhancing the salience of the inner aperture might allow children to attend to this shape more easily.

Congruent compound objects may reduce the need for selective attention. Recall that the congruent objects had an aperture and solid surround of the same shape (e.g., circular aperture embedded in a circle). Because the aperture and surrounding shapes are the same, there is no need to inhibit responses to the shape of the solid surround, which may allow children to more easily match the congruent object to the tower. We explored this possibility by examining the effects of congruency on successful selections.

Congruency effect. The present study indicates that the congruency of the compound object influences children's actions. In the tower selection condition, success was significantly affected by congruency, demonstrated by the Age x Congruency interaction. Children became more successful at younger ages with congruent objects compared to incongruent objects. While success with congruent objects began to exceed chance levels around 22 months, success with incongruent objects did not exceed chance responding until the 26^{th} month. Simply stated, congruent objects are easier for children to match to a corresponding tower than incongruent objects.

In addition to the influence of congruency on success in the tower selection condition, we also found that the congruent objects were selected more frequently in the object selection task. Recall that children were presented a subset of trials in the object selection condition in which all three of the compound objects had apertures that matched the tower. Children had to choose one of the three compound objects, even though all three would successfully fit on the tower. We found an Age effect, such that younger children selected incongruent compound objects more frequently, while older children selected congruent compound objects more frequently. Taken together, the Congruency Effect suggested by the results illustrates that congruency not only affects success, but also boosts selection.

Although we have demonstrated that congruency influences children's actions, we do not know if children are matching the congruent compound objects based on the internal aperture shape or the shape of the solid surround. It could be that the congruency of the compound object directs children's attention to the negative space of the aperture, because there is no conflict between the shape of the aperture and the shape of the solid surround. Alternatively, the lack of conflicting information between the shapes of the inner aperture and solid surround could result in children focusing on the external shape. This would fortuitously direct children to make the correct match, as the solid surround shape is the same as the inner aperture shape, and would therefore match the tower. Continuing to examine on what basis matching occurs will be important to form a more complete understanding of how children relate apertures to objects.

Future Directions

The findings of the present study suggest that differences in selective attention are affecting the ways in which children respond in fitting tasks. Our results point to new directions for fitting research. At present, it is unknown if children match congruent objects based on the inner aperture shape or the solid surround shape. Future studies might utilize eye tracking to test these possibilities more directly. Specifically, researchers using eye-tracking would be able to determine whether children are attending to the inner aperture or the solid surround of congruent compound objects and how this influences responding. This type of study could potentially lead to additional understanding of the processes that underlie selective attention.

Selective attention measures. Although the DCCS is a valid and reliable selective attention measure for children beginning at 3 years of age (Zelazo et al., 2013), there is not currently a widely accepted measure for children under 3. Future studies might therefore consider adapting the current fitting task to develop a measure of selective attention for children below age 3. Further variations to the current task might include changes to the salience of the inner aperture shape. For example, lining the boundary of the inner aperture in a different color than the solid surround (especially if that different color matches the color of the tower) could increase the salience. Alternatively, using objects and towers that are all the same color or using objects that are constructed out of a clear plastic material could decrease the saliency of the aperture. Changes such as these might influence the dimension to which children attend. Investigating these types of task variations might offer measures of how to boost or tax selective attention.

Developmental patterns. Another issue raised by the present study concerns the developmental relation between matching negative to positive space and vice versa. Our findings, in conjunction with findings from past research (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Shutts et al., 2009) provide indirect evidence that children acquire the ability to match negative to positive space later than positive to negative space. Comparing the abilities to match negative to positive space, and positive to negative space within the same children would test this suggested developmental sequence more directly.

Future research should also consider developmental differences that may emerge based on the orientation of the compound objects. The objects we presented to children were initially aligned with the tower, thus potentially requiring children to employ mental translation but not mental rotation. Varying the orientation of each the inner aperture shapes and the solid surround shapes would require children to employ both mental rotation and translation, and developmental differences might emerge. In addition to potential developmental differences, it would also be interesting to look at potential sex differences that may emerge when varying orientation. Though no sex differences were found in the current study, findings from past research are mixed (Frick & Wang, 2014; Levine, Huttenlocher, Taylor, & Langrock, 1999; Möhring & Frick, 2013; Quinn & Liben, 2008). Some studies have found sex differences in mental rotation tasks with infants (Quinn & Liben, 2008) and children older than 4.5 years (Levine et al., 1999), while others have found no differences at age 3 (Frick, Hansen, & Newcombe, 2013). Directly examining the influence of orientation could potentially provide more information regarding both developmental patterns and possible sex differences.

Spatial training. Finally, future studies should also explore whether fitting can be enhanced with training. Despite the importance of early shape fitting and object assembly abilities with regard to later academic outcomes, particularly in STEM related areas (Grissmer et al., 2013; Newcombe, 2010; Verdine et al., 2014, Verdine et al., 2017), less is known about effective ways to promote these types of spatial abilities. For instance, it is unknown if training in negative to positive space fitting would generalize to positive to negative space fitting, or vice versa. Based on our findings that the ability to match negative space to positive space develops later, it is reasonable to expect training on both types of fitting would be necessary, but these are possibilities that should be investigated.

Additionally, some evidence suggests that structured, play-based activities (e.g., block building, puzzles) can improve visuospatial skills such as fitting (Casey et al., 2008; Grissmer et al., 2013; Jirout & Newcombe, 2015). But are certain types of activities more or less effective than others? Research on the effectiveness of spatial training and spatial games would provide insight into how spatial skill development can be promoted in preschool-aged children and whether such training enhances fitting (both positive to negative space and negative to positive space).

The availability of spatial activities for different populations should also be considered, as this may vary by socioeconomic status. Past work has found that children from low SES homes score lower on measures of spatial abilities than their middle and high SES peers (Jirout & Newcombe, 2015; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005; Nesbitt, Baker-Ward, & Willoughby, 2013). SES has been found to influence spatial ability in children as young as three (Verdine et al., 2014), and it is important to note that participants in the current study are predominately White children from higher SES homes. Research that includes a broader and more diverse sample of children would be especially helpful to further our current understanding of the development of fitting abilities in children

Conclusions

The present study has demonstrated that children have more difficulty relating negative to positive space than they do relating positive to negative space. This difficulty is likely influenced by the shapes of the compound objects, particularly the shape of the inner aperture in relation to the shape of the solid surround. The conflicting shapes of incongruent objects, created by the opposing inner aperture and solid surround shapes, may affect the part of the compound object to which children attend. This, in turn, likely influences the ways in which children understand and act on the compound objects in relation to other objects in the environment.

More broadly, the current study provides new information about the ability of children to solve object fitting tasks. By examining the development of matching negative space to positive space, we have extended previous findings on object fitting (Jung et al., 2015; Örnkloo & von Hofsten, 2007; Shutts et al., 2009) and have shown that when negative space is embedded in positive space, fitting requires children to understand and then act on the shape of the aperture in relation to the shape of the solid surround. Additionally, we have shown that understanding the shape of the aperture in relation to the shape of the solid surround is an ability that may be difficult for children. Fitting an aperture to an object appears to develop later than fitting objects into apertures. The current study, together with past fitting work, presents a more comprehensive picture of how object fitting develops in young children.

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Biography

Blair Youmans was born in Columbia, South Carolina and raised in various cities throughout the southeast. She attended Agnes Scott College in Decatur, Georgia where she received a Bachelor of Arts in Psychology. During her time at Agnes Scott, Blair created and ran a recreational therapy program for children diagnosed with autism. Upon graduation, she began teaching at a small private school for children with neurodevelopmental diagnoses. In 2015, Blair joined the Infant and Toddler Development Project at Tulane University as a doctoral student in Psychological Sciences. Her research interests are focused on sensorimotor development in young children. Blair anticipates continuing this line of research while working toward her Doctor of Philosophy in Psychological Sciences.