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Development of Three-Dimensional Completion of Complex Objects

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Three-dimensional (3D) object completion, the ability to perceive the backs of objects seen from a single viewpoint, emerges at around 6 months of age. Yet, only relatively simple 3D objects have been used in assessing its development. This study examined infants' 3D object completion when presented with more complex stimuli. Infants ($N = 48$) were habituated to an "L"-shaped object shown from a limited viewpoint; then they were tested with volumetrically complete (solid) and incomplete (hollow) versions of the object. Four-month-olds and 6-month-old girls had no preference for either display. Six-month-old boys and both sexes at 9.5 months of age showed a novelty preference for the incomplete object. A control group ($N = 48$), only shown the test displays, had no spontaneous preference. Perceptual completion of complex 3D objects requires infants to integrate multiple, local object features and thus may tax their nascent attentional skills. Infants might use mental rotation to supplement performance, giving an advantage to young boys. Examining the development of perceptual completion of more complex 3D objects reveals distinct mechanisms for the acquisition and refinement of 3D object completion in infancy.

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Infancy research, over the past three decades, has grown in its understanding of the influences of task demands on infants' performances in a variety of cognitive and perceptual experiments. For example, success on Piaget's A-not-B task does not solely reflect object permanence, as Piaget (1954) surmised. Rather, success or failure depends on a host of factors related to infants' inhibitory control (Diamond & Doar, 1989), memory (Munakata, 1998), exploration history (Thelen, Schoner, Scheier, & Smith, 2001), cognitive capacity (Berger, 2004), and the response criterion (Cuevas & Bell, 2010). Probing break downs in performance, as related to task demands, is an ideal way to explore the cognitive architecture underlying a specific ability and as a way to more deeply examine its developmental mechanisms.

In the current study, we explore break downs in infants' object perception: specifically, the perception of an object's back side despite seeing it from a single viewpoint—termed three-dimensional (3D) object completion (Soska & Johnson, 2008). In this case, we altered the complexity of the test stimulus compared with the previous work. We predicted that infants in an age group previously displaying 3D object completion would now fail to show it. Moreover, we posit that the mechanism driving the initial acquisition of 3D object completion is distinct from the mechanisms supporting its further development.

Perceptual completion of three-dimensional objects

The visual environment is filled with objects moving behind and in front of one another, nearer objects blocking further objects, and front sides of objects blocking their back sides from immediate view. Yet, adults easily and readily perceive the world as made of persisting forms and solid objects positioned sensibly in depth. The process by which observers perceive objects as whole, solid, and enduring despite the fragmented nature of the visual array is perceptual completion (e.g., Kellman & Shipley, 1991). For the case of 3D object completion, adults effortlessly perceive that 3D objects—whose fronts occlude their backs (the problem of self-occlusion)—will have a back side and form reasonable percepts of what this back side looks like (van Lier, 1999; Tse, 1999b).

The wedge-shaped form in Figure 1a is most likely perceived as having a complete back side similar to that shown in Figure 1b but not the hollow back side shown in Figure 1c. As a first step toward volume perception, observers must relate the edges and surfaces of the object to each other (Tse, 2002). This wedge shape represents a simple case for 3D object completion, because it only has two visible surfaces (van Lier &

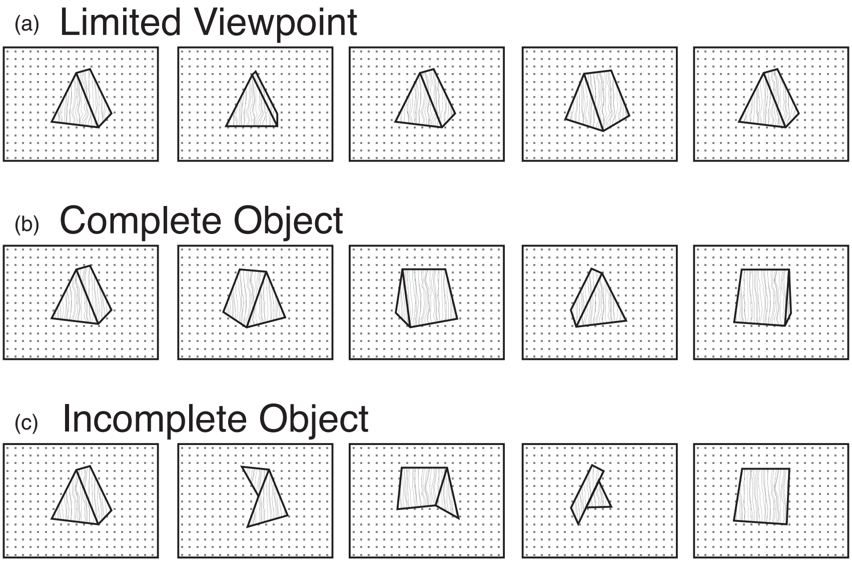
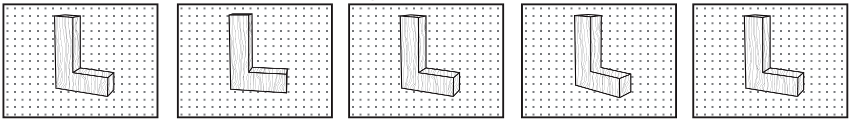


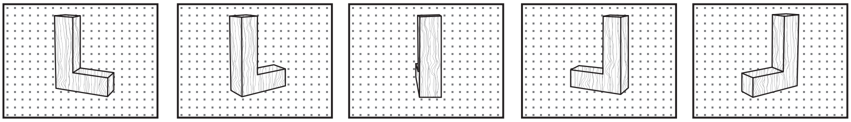
Figure 1 Example of simple three-dimensional object used in the previous research on 3D object completion in infants. (a) The wedge-shaped object seen from a single viewpoint. (b) The object rotated in depth counterclockwise showing that its back side is solid and complete (c) The object rotated in depth counterclockwise showing that its back side is hollow and incomplete.

Wagemans, 1999; Vetter & Poggio, 1994). The second step is binding these surfaces to form volumes (Tse, 1999a), which is straightforward for the wedge shape, because it only produces a single volume.

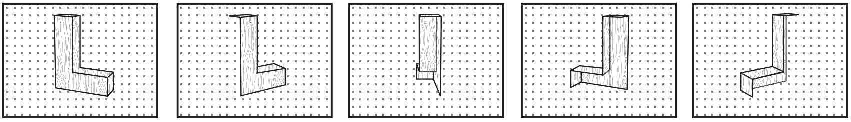
More complex forms, however, can pose a challenge to the adult visual system (van Lier, 1999) and to computer software designed to recapture the 3D form of an object from a single viewpoint (Breckon & Fisher, 2005). In cases where there are multiple surfaces that need to be related or where these related edges form several intermediary volumes, perceptual completion can take longer (van Lier & Wagemans, 1999) or simply fail (Breckon & Fisher, 2005). For example, the "L"-shaped object (hereafter denoted as the *L-object*) in Figure 2a has more front surfaces compared to the wedge shape. Moreover, there are now two intermediary volumes to be connected: the tall rectangular shape and smaller rectangle at its front. While adults would readily to perceive the back side as similar to that shown in Figure 2b, as opposed to the hollow form in Figure 2c, the computational process takes longer and is more involved (van Lier, 1999).



(a) Habituation Display



(b) Complete Test Display



(c) Incomplete Test Display

Figure 2 Sketch of the complex, L-object used in the current study. (a) During habituation, infants were shown the object pivoting 15° left and right in depth around the vertical axis, though only saw a single viewpoint. (b) At test, the complete object was seen from a full 360° rotation counterclockwise; it had a filled back side, extended from that seen from the limited viewpoint. (c) At test, the incomplete object was also seen from a 360° rotation but had a hollow, missing backside.

Development of perceptual completion in infancy

Although adults' perceptual completion is often effortless and relatively quick (Murray, Sekuler, & Bennett, 2001), even for complex 3D forms (Tse, 1999b), little is known about how infants deal with the problems imposed by self-occluded object surfaces. We do know that 3D object completion does not emerge until after 4 months of age (Soska & Johnson, 2008) when infants are tested with computer-generated 2D displays like those seen in Figure 1. In this task, infants were habituated to the front view of an object (similar to Figure 1a) that rotated 15° left and right in depth around the vertical axis. Once infants were habituated, they were shown complete and incomplete 3D objects in alternation (similar to Figures 1b, c respectively). Longer looking toward the incomplete test display was assumed to reflect a posthabituation novelty preference, indicating that the limited-view object seen during habituation was perceived as a complete volume. Infants at 4 months of age showed no differences in looking times to the two test displays, but infants at 6 months of age looked longer at the incomplete display. Infants in a control group shown only the test displays showed no looking preference, ruling out the possibility of a spontaneous preference for either the solid, complete form, or the hollow, incomplete form.

By 4 months of age, infants are sensitive to the kinetic and static depth cues needed to perceive 3D structure in 2D displays. Infants can use kinetic information to extract 3D structure (Arterberry & Yonas, 1988) and are sensitive to line junctions ("T," "Y," and "arrow" junctions) and shading as cues to objects' 3D structure (Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Shuwairi, Albert, & Johnson, 2007). Thus, local static and kinetic depth cues are likely not sufficient to drive differential responding to complete and incomplete 3D object completion displays at 4 months of age (Soska & Johnson, 2008). However, the addition of ground plane cues and additional shading to the habituation and test displays can improve 3D object completion in 4.5-month-old infants—perhaps by lowering the threshold for global volume perception (Vrins, Hunnius, & van Lier, 2011). So, while local depth cues may help infants extract 3D form from limited viewpoint displays, there appears to be another level of global processing that supports perception of objects' back sides.

Infants have been shown to learn to perceive the back side of limited-view objects through their own experiences sitting up and manipulating objects while looking at them (Soska, Adolph, & Johnson, 2010). Infants between 4.5 and 7.5 months of age completed a replication of the procedure by Soska and Johnson (2008) along with a motor skill assessment. Only the infants who could sit independently, without using their hands for support, were able to rotate objects, run their fingers along objects' surfaces, and transfer objects from hand to hand while looking at the objects. These are exactly the kind of behaviors that provide infants with active control over viewing the back sides of objects. In turn, the frequency of visual–manual object exploration predicted infants' looking preferences in the habituation task: Infants who more frequently generated visual and tactile exploration of objects were those who showed positive evidence of 3D object completion. Importantly, the objects that the infants explored in the motor skill assessment were not similar to those seen in the habituation task, and half of the infants did the habituation task before doing the motor skills assessment. What this means is that infants' repertoires of exploratory activity, in place prior to testing in the lab, predicted their perceptual completion skill under tested conditions. The infants who presumably had more day-to-day experiences visually and manually exploring the back sides of objects showed evidence of perceiving the back side of a limited-view object.

These studies illuminate the onset of 3D object completion in infancy and tell us something about the mechanisms by which it is acquired, but tell us little about its limits and scope once it becomes operational. All of the previously mentioned studies used the simple wedge-shaped object shown in Figure 1. When the display objects are changed to a more complex volume, such as that in Figure 2, how would infants respond? Presumably, the speed and success of perceptual completion would be jeopardized, as in the work on adults and computer models (Breckon & Fisher, 2005; van Lier & Wagemans, 1999).

Moreover, we had good reason to expect a different developmental trajectory for infants' 3D completion of more complex objects, given related work on perceptual completion of occluded objects in 2D displays. When 4-month-old infants are shown a moving, vertical rod occluded by a box, they perceive the top rod piece as continuing behind the box and joining up with the bottom rod piece, giving evidence of perceptual completion (Kellman & Spelke, 1983). Newborn infants, however, do not perceive the moving rod pieces as being joined (Slater, Johnson, Brown, & Badenoch, 1996). Interestingly, perception of the two occluded rod pieces being joined at 2 months of age depends on the characteristics of the rod and box display (Johnson & Aslin, 1995). When the occluding box is altered to show more of the rod, 2-month-olds will show evidence of perceptual completion; when the box is large, as in the studies with 4-month-olds (e.g., Johnson & Aslin, 1996; Kellman & Spelke, 1983), then the 2-month-olds will not perceptually complete the rod. If younger infants are required to relate the edges of an object across a long distance, perceptual completion breaks down (Smith, Johnson, & Spelke, 2003). Similarly, when 4-month-old infants see a ball moving back and forth on a trajectory that is partly obscured by a box, they will only perceive that the ball continues to exist behind the box if the box is small (Johnson, Amso, & Slemmer, 2003a; Johnson, Bremner, Slater, & Mason, 2003b). If the ball is hidden behind the box for too long a distance, infants at 4 months of age will not perceptually complete its trajectory, nor will they perceive the trajectory as continuous if it is oblique relative to the box and stimulus display (Bremner et al., 2007). Perceptual completion is more robust by 6 months of age: Infants perceived the ball as continuous behind the occluding box regardless of the occluder's size.

These studies demonstrate that infants' perceptual completion abilities are affected by stimulus characteristics and that perceptual completion abilities undergo incremental development after their initial appearance. The encoding of perceptual information needs to occur in more robust and enduring ways for infants to contend with more complex stimuli (Cohen, Chaput, & Cashon, 2002; Johnson, 2010a). Perceptual learning can help mitigate the effects of stimulus complexity on object completion. For example, when infants are trained to anticipate the bouncing ball emerging from behind the occluding box, 4-month-olds now show evidence of perceptual completion of the ball's trajectory (Johnson & Shuwairi, 2009). Yet, this effect is short-lived and does not withstand even a 30-min delay. Long-term improvements in object completion wait for permanent changes in infants' visual-cognitive systems.

The current study

We expected that infants' 3D object completion would be affected by changes in relevant stimulus properties. For completion behind an occluder (e.g., the rod and box display), a relevant property is the size of the occluder over which related edges must be tracked (Kellman & Shipley, 1991; Tse, 2002). For 3D object completion, we reasoned that two stimulus properties relevant to success at the task are the number of edges to be completed (van Lier & Wagemans, 1999) and the number of intermediary volumes made by these edges (Tse, 1999b). In this study, we used the complex L-object described previously (see Figure 2) in a habituation procedure identical to those used in previous work (Soska & Johnson, 2008; Soska et al., 2010; Vrins et al., 2011). Additionally, we tested a group of infants in a control task designed to assess infants' spontaneous preference for either the incomplete or complete L-object test displays. We observed infants at 4, 6, and 9.5 months of age to explore the developmental progression of 3D object completion with a complex stimulus.

The L-object presents a left–right asymmetry that may offer an opportunity to examine sex differences in infant performance, because of a male advantage in mental rotation of complex objects that has been revealed in infants as young as 3 months. Infants in these studies were observed for evidence of discrimination between a familiarized complex object seen in a novel (rotated) position and a mirror image of that object. The experiments revealed a sex difference in behavior: 5-month-old males looked longer at the mirror-image stimulus over the familiar stimulus, even though neither test stimulus had previously been seen (Moore & Johnson, 2008; Quinn & Liben, 2008); 3-month-old males looked longer at the familiar (Moore & Johnson, 2011). In contrast, female infants looked at the two test stimuli for approximately equal durations. The male infants' preferences were interpreted to mean that they recognized the familiar object, even though it was now being seen in a novel position, and discriminated it from its mirror image. In this study, we reasoned that 3D object completion with a relatively complex stimulus might likewise be observed first in males, if performance in this task relies on remembering 3D form of the habituation display and reacting to the novelty of the test displays now viewed from a new vantage point in 3D space—two cognitive operations that are thought to be involved in mental rotation (Zacks, 2008).

METHOD

Participants

The final sample consisted of thirty-two 4-month-olds (*M* = 4.04 months, *SD* = 0.33), thirty-two 6-month-olds (*M* = 5.95 months, *SD* = 0.29), and thirty-two 9.5-month-olds (*M* = 9.62 months, *SD* = 0.50)—with 16 girls and 16 boys in each age group. Data from an additional 18 infants were collected but excluded because of fussiness (11 infants), persistent inattention to the monitor (five infants), falling asleep (one infant), and parental interference (one infant). Families were recruited from commercial mailing lists and public birth records. Most families were middle class and Caucasian. All infants were healthy and born at term. Infants received small toys and *t*-shirts as compensation for participating.

Stimuli

Infants watched displays of a computer-generated L-object (see Figure 2 for a sketch of the stimuli) similar to those used in the previous studies on 3D object form perception in infants (Soska & Johnson, 2008; Soska et al., 2010). The L-object subtended a maximum visual angle of 8.5 (height) and 11.5° (width) and was rendered with a brown, wood-like surface to accent its contours. Objects in the displays were presented against a 12 × 20 grid of white background dots. During the habituation phase, the object was presented from a limited viewpoint (Figure 2a): It pivoted left and right 15° in depth around the vertical axis, taking 4 sec to complete a full pivot in both directions and return to center. In the test trials, objects in the displays rotated a full 360° about the vertical axis, revealing their back sides. The complete object view (Figure 2b) was an L-object with a complete back and sides (the object looked like an "L"-shaped toy block). The incomplete object view (Figure 2c) consisted only of the faces seen during habituation with a hollow back side. The test displays took 10 sec to make a full rotation and return to center. In informal pilot testing, adults reported that all of the displays looked like rotating 3D objects.

Procedure

Infants sat on their parents' laps approximately 120 cm away from a 76-cm monitor in a darkened room. An experimenter, who was out of sight behind a divider, observed infants' faces on a closed-circuit camera and recorded their looking patterns on a Macintosh computer running Habit software (Cohen, Atkinson, & Chaput, 2000). On the basis of the experimenter's online coding, the computer presented the stimulus displays, calculated the habituation criterion for each infant, and changed displays after the criterion was met.

Before the beginning of each trial, an attention-getter (an expanding and contracting ball paired with a series of tones) was used to attract infants' gaze to the center of the screen. As soon as infants fixated the screen, the attention-getter was replaced with the experimental stimulus and timing of trials began. Trials ended when infants looked away for 2 sec or until they had accumulated 60 sec of total looking. After the end of each trial, the attention-getter was shown again, followed by the start of a new trial.

We used an infant-controlled habituation method: The limited-view, L-object habituation display was shown until infants' total looking time during four consecutive trials summed to less than half of the total looking time to the first four trials. Consequently, infants watched the habituation display a minimum of five habituation trials. If infants did not reach the habituation criterion after 12 trials, the test displays were shown anyway. Infants watched the two test displays three times each in alternation—the order of presentation of the test displays was counterbalanced across the sample. In the control task, infants only watched the two test displays (three times each in alternation) without first viewing the limited-view display. We randomly assigned infants to the habituation ($N = 48$ infants) or control task ($N = 48$ infants).

We determined the reliability of the experimenter's online judgments by having a second coder score looking times from video tapes for 33% of the infants in the habituation task. The Pearson correlation between the online and offline judgments was .97 for total duration of looking per trial.

RESULTS

Data consisted of the total duration of looking to habituation and test displays on each trial. Exploratory analyses confirmed that the data were approximately normally distributed, and variances were equal across groups—meeting the requisites to use an analysis of variance (ANOVA).

Habituation performance

Initial analyses examined age and sex differences in looking data during the habituation phase of the experiment. We first performed a series of 3 (age group: 4, 6, 9.5 months) × 2 (sex: girls, boys) ANOVAs on four variables reported in Table 1: the number of trials to habituate, total looking times during habituation, the average of each infant's looking times during the

TABLE 1
Data from the habituation phase for the three age groups tested

Age	*Trials to habituation criterion*	*Total looking time during habituation*	*Mean looking in first 4 trials*	*Mean looking in last 4 trials*
4 months	7.5 (2.9)	80.7 (31.6)	13.4 (6.8)	7.3 (4.1)
6 months	9.3 (2.4)	120.4 (67.9)	17.2 (10.4)	8.9 (4.1)
9.5 months	8.4 (2.8)	148.1 (150.5)	18.5 (13.6)	10.5 (9.8)

Numbers in parentheses are SDs.

first four trials, and the average of each infant's looking times during the last four trials. (These four analyses included nonhabituators.) There were no reliable main effects or interactions in any of these analyses (*F*s < 3, *p*s > .05). All infants reached the habituation criterion described previously except three 4-month-olds, five 6-month-olds, and four 9.5-month-olds; a Fisher's exact test revealed no reliable age differences in the numbers of infants who habituated, $p = .91$. Finally, a 3 (age group: 4, 6, 9.5 months) × 2 (nonhabituators versus habituators) ANOVA on test trial preference data (i.e., proportion of looking at the incomplete object at test) revealed a statistically significant main effect of age group ($F(2, 42) = 4.31$, $p < .05$, partial $\eta^2 = .17$), reflecting age differences in looking at the incomplete versus complete test stimuli (discussed in detail in the following sections), and no other reliable effects. In summary, these analyses reveal little in the way of influences from habituation performance on test trial looking times, nor any reliable age or sex differences in habituation performance.

Test trial performance

Preliminary analyses indicated no reliable effects of order of presentation of test displays. The only effect of test trial block (first, second, third viewing of test display) was a decrease in looking time across the three trials; so, looking times were averaged across the three trials for each test display. When follow-up testing was needed, the Bonferonni adjustment was used to correct for multiple pairwise comparisons.

We performed a 2 (task: habituation, control) × 3 (age group: 4, 6, 9.5 months) × 2 (sex: girls, boys) × 2 (test display: complete, incomplete object) mixed-design ANOVA—with task, age group, and sex as between-participant factors and test display as a within-participant factor. The analysis revealed a significant main effect for task ($F(1, 84) = 12.44$, $p = .001$, $\eta^2 = .15$), because of longer looking toward the test displays in the control task compared with the habituation task. We also found a significant main effect of test display ($F(1, 84) = 11.85, p = .001, \eta^2 = .14$), stemming from longer looking at the incomplete display compared with the complete display overall. This test display main effect was mediated by interactions with task ($F(1,84) = 18.06, p < .001, \eta^2 = .22$) and with age group ($F(2, 84) = 3.72, p = .028, \eta^2 = .09$), but importantly, a three-way interaction between task, age group, and test display ($F(2, 84) = 3.27, p = .043, \eta^2 = .08$). We also found a marginal four-way interaction between task, age group, sex, and test display ($F(2, 84) = 2.87, p = .063, \eta^2 = .07$). (Our observed power for this four-way interaction was .6, and the effect size was medium; because of the sizable variance in the control task (see Figure 3b), especially in the younger infants, this interaction was only marginally statistically significant in the omnibus model). Below, we first address the differential responding to the test display by task and age group. Next, because we had reason to suspect sex might matter with our stimuli (Moore & Johnson, 2008, 2011), we follow-up on the interaction with infants' sex.

Effects of task and age

Figure 3 shows infants' mean looking times to the two displays in the habituation (Figure 3a) and control tasks (Figure 3b) in the 4-, 6-, and 9.5-month-old age groups. In the habituation task, an age group × test display ANOVA revealed a significant interaction between age group and test display ($F(2, 45) = 5.43, p = .008, \eta^2 = .24$). Follow-up comparisons confirmed there was no reliable difference in looking times to the two test displays at 4 months of age ($p > .1$). At 6 months of age, looking was marginally longer toward the incomplete display ($p = .04$); however, the significance of the test did not exceed the correction for multiple comparisons ($\alpha \cong .0167$). By 9.5 months of age, there was a clear and reliable preference for the incomplete test display ($p < .001$).

In the control task, the age group × test display ANOVA confirmed no main effect of test display ($F(1, 45) = 0.38, p > .1$) and no interaction between age group and test display ($F(2, 45) = 1.1, p > .1$). Follow-up comparisons confirmed there were no reliable preferences for either test display in any age group in the control task (ps $> .1$).

Effects of task, age, and sex

Figure 4 displays infants' mean looking times for boys and girls at 4, 6, and 9.5 months of age. We followed up the marginal four-way interaction between task, age group, sex, and test display (presented above) with 3 (age group: 4, 6, 9.5 months) × 2 (sex: girls, boys) × 2 (test display: incomplete,

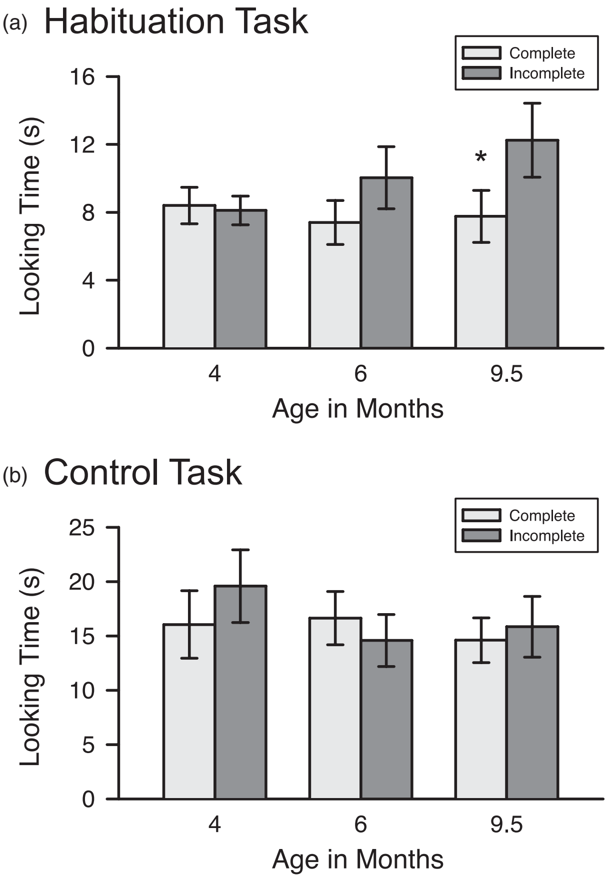


Figure 3 Mean looking times to the complete and incomplete test displays at 4, 6, and 9.5 months of age. (a) In the habituation task, 4-month-olds showed no preference for either test display, 6-month-olds showed a weak preference for the incomplete display, and infants at 9.5 months of age showed a reliable preference for the incomplete display (*indicates $p < .015$). (b) Infants in the control task showed no significant differences in looking times at any age. Error bars represent standard errors of the mean.

complete object) mixed-design ANOVAs within the habituation and control tasks. In the habituation task, there was a significant three-way interaction between age group, sex, and test display ($F(2, 42) = 3.93$, $p = .027$, $\eta^2 = .19$). To follow up this interaction, we performed separate 2 (sex: girls, boys) × 2 (test display: incomplete, complete object) interaction contrasts within each age group. The analyses confirmed no interactions in the 4- or 9.5-month-olds ($Fs(1, 42) = .13$, $ps > .1$), but there was a sex × test display

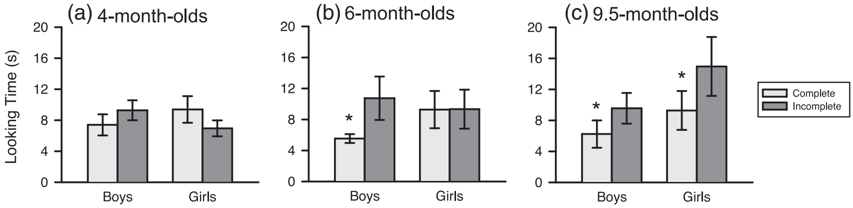


Figure 4 Mean looking times to the incomplete and complete test displays in the 4-, 6-, and 9.5-month-old boys and girls in the habituation task. (a) Neither boys nor girls showed a reliable looking preferences at 4 months of age. (b) At 6 months of age, only the boys looked significantly longer toward the incomplete test display (*indicates $p < .015$). (c) By 9.5 months of age, both the boys and girls looked reliably longer at the incomplete display (*indicates $p < .015$). Error bars represent standard errors of the mean.

interaction at 6 months of age ($F(1, 42) = 10.52$, $p = .002$, $\eta^2 = .25$). There were no significant differences in looking times to the test displays in 4-month-old girls or boys ($p\text{s} > .1$). There was no reliable looking preference by 6-month-old girls ($p > .1$), but we found significantly longer looking toward the incomplete display in 6-month-old boys ($p = .001$). We also found reliably longer looking toward the incomplete display in the 9.5-month-old girls and boys ($p\text{s} < .001$).[1] All but one of the boys at 6 months of age looked reliably longer at the incomplete display compared with the complete display, so looking preference was not unanimous as a group but was reliably different from chance (Wilcoxon signed-rank test, $Z = 2.24$, $p = .025$). On the other hand, the 6-month-old girls showed no consistent direction in their looking preferences ($Z = 0.14$, $p = .89$). By 9.5 months of age, all of the boys and girls looked longer to the incomplete test display ($Z\text{s} = 2.52, p\text{s} = .012$).

In the control task, there were no reliable effects of test display, age group, or sex ($F\text{s} < 1, p\text{s} > .1$). Lastly, we directly compared infants' looking times in the habituation and control conditions for each age group and each sex with 2 (task) × 2 (test display) ANOVAs. We found no effect of

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[1] While boys and girls at 9.5 months of age showed a novelty preference for the incomplete display, the girls' overall looking toward the two test displays was greater than the boys. Girls at 9.5 months of age took slightly longer to habituate ($M = 9.37$ trials for girls, $M = 7.37$ for boys), and girls' looking times were greater than boys' on the last habituation trials ($M = 12.93$ sec for girls, $M = 6.83$ sec for boys). When the metric to assess novelty preferences was recovery in looking time from the last habituation trials to each test display, the preferences for the incomplete display persisted ($t\text{s} > 3.05$, $p\text{s} < .02$). This age group was the only one to show any noticeable divergence in overall looking between boys and girls, which did not impact infants' novelty preferences.

condition in the 4-month-olds or 6-month-old girls (Fs(1, 14) > 1.5, ps > .1). There was a reliable interaction in the 6-month-old boys (F(1, 14) = 5.05, p = .041, η^2 = .36) and both groups of 9.5-month-olds (Fs(1, 14) > 8.00 ps < .015, η^2s > .57)—stemming from differential looking to the incomplete displays (but not the complete displays) driven by the habituation task (ps < .05).

DISCUSSION

Perceiving the back sides of objects seen from a limited viewpoint—3D object completion—develops at around 6 months of age (Soska & Johnson, 2008) and emerges in concert with coordinated visual-manual exploration (Soska et al., 2010). Yet, as this visual-cognitive ability has only been recently studied, little is known about the processing limits of 3D object completion in infants. The current study demonstrates that 3D object completion of more complex 3D forms (relative to the previous studies) requires further development. Infants at 4, 6, and 9.5 months of age viewed a 3D "L" shape from a single viewpoint. After habituating to the limited-view object, infants saw the full vantage of either a solid, complete volume or an incomplete, hollow façade. Longer looking toward the incomplete display would imply that infants perceived the limited-view object as a complete volume and viewed the incomplete object as novel (see Soska & Johnson, 2008).

Only at 9.5 months of age did infants show robust perceptual completion of the more complex 3D form. At 6 months, boys but not girls displayed evidence of perceiving the back side of the L-object, in parallel with recent work suggesting early advantages in spatial perception for infant boys (Moore & Johnson, 2008, 2011; Quinn & Liben, 2008). Four-month-olds showed no evidence of 3D object completion, even in boys. Infants in a control task, only shown the incomplete and complete test displays, showed no spontaneous preference. Infant performance in 3D object completion tasks, therefore, is affected by a combination of stimulus complexity, infants' sex, and age.

Stimulus complexity and the mechanisms of object completion

The present findings that the developmental trajectory for perceptual completion of relatively complex L-objects differs from the previously reported developmental trajectory for simpler wedge objects has implications for the mechanisms behind the development of volume perception in infancy. Like other forms of perceptual completion (Johnson & Aslin, 1996; Johnson et al., 2003a,b; Kellman & Spelke, 1983), infants achieve 3D object completion through a process presumably similar to that in adults: encoding and binding local edges to form volumes and in turn binding those local volumes to generate a global form (Tse, 1999b). Thus, the amount of edge and surface information affects the speed of perceptual completion (van Lier & Wagemans, 1999), and attention to and manipulation of multiple features determine whether 3D object completion succeeds at all (Breckon & Fisher, 2005). Complex object completion might fail in young infants because of an inability to manage multiple sources of local perceptual information and bind it into a coherent whole (Cohen et al., 2002). Simple 3D objects may be readily perceived as full volumes because of lower demands placed on information acquisition and processing skills (van Lier & Wagemans, 1999). In support of this idea, Vrins et al. (2011) found that when additional local features (shading and a ground plane) were added, and thus demands on feature extraction were lowered, infants' object completion improved at 4.5 months of age. Eye-tracking data could help elucidate the degree to which attention to relevant local features correlates with infants' performance in 3D object completion tasks.

In addition, mechanisms of 3D object completion may not be strictly perceptual and could rely on some form of mental rotation (Koning & van Lier, 2004; van Lier, 1999). The use of mental rotation might be especially prevalent when the number of image features or objects is large (Koning & van Lier, 2004). When infants' ability to track multiple edges and surfaces is immature and compromised by stimulus complexity, they could potentially engage mental rotation to boost performance. The 9.5-month-olds in the current study presumably had well-developed feature binding (e.g., Csibra, Davis, Spratling, & Johnson, 2000) and attentional skills (Colombo, 2001) and appeared to succeed at 3D object completion despite the complexity of the L-object. For the 6-month-olds, however, for whom these skills are relatively underdeveloped, success may have depended more on the degree to which mental rotation could be used to guide perceptual completion. An important avenue for future research on 3D object completion would be directly comparing infants' performance in mental rotation tasks and perceptual completion tasks at 6 and 9 months of age.

Sex differences and the development of visual cognition

The role that mental rotation plays in 3D object completion also may help account for the sex difference found at 6 months of age. There is growing support for the claim that there is a male advantage in infants' spatial perception and mental rotation (Moore & Johnson, 2008, 2011; Quinn & Liben, 2008). If infants needed to use mental rotation as a backup for less-mature feature binding in the current study, then we might expect that boys would outperform girls. The sex difference we found at 6 months of age provides support for the possibility that mental rotation is the dividing factor in infants' 3D object completion at 6 months. And infants' sex differences are likely confined to mental rotation in the current study, because motor skills did not differ by sex in the data presented by Soska et al. (2010). This male advantage is especially important in light of the general (although modest) developmental trend in early perceptual and cognitive capacities that tend to favor females, including such functions as stereopsis (Thorn, Gwiazda, Cruz, Bauer, & Held, 1994), visual acuity (Gwiazda, Bauer, and Held (1989), object discrimination (Overman, Bachevalier, Schumann, & Ryan, 1996), and physical reasoning (Kotovsky & Baillargeon, 1998).

Sex differences in mental rotation, however, are not entirely straightforward. Sex alone is not an explanatory factor; rather, it reflects differences in the underlying visual-cognitive system related to mental rotation. The neural underpinnings of mental rotation can be masculinized by exposure to testosterone (Gouchie & Kimura, 1991; Moffat & Hampson, 1996). Women with male co-twins, who were thus exposed to higher intrauterine levels of testosterone than women with female co-twins, show better performance on mental rotation tasks (Vuoksimaa et al., 2010). The epigenesis of advantages in mental rotation in infant boys is part of a complex developmental history. Additionally, early sex differences are not always robust or enduring (Spelke, 2005). Indeed, our results show that this early advantage for boys disappears by 9.5 months of age.

Development of 3D object completion as a system

We contend that 3D object completion emerges in infancy as part of a developmental system, where no single factor holds sway (Gottlieb, 2007). Multiple mechanisms play a role in the development of 3D object completion. The initial instigator is hands-on perceptual experiences, driven by learning to sit up and explore objects visually and manually (Soska et al., 2010). Infants learn that objects have back sides in general, by picking them up, turning them over, and looking at their backs. Other related studies also affirm the importance of object exploration for individuating objects (Needham, 2000; Wilcox, Woods, Chapa, & McCurry, 2007) and perceiving others' goals with objects (Sommerville, Woodward, & Needham, 2005). This initial learning about 3D object form from object exploration sets the stage for later perceptual completion of more complex objects, but it is not sufficient for complex object completion.

Other, tangential mechanisms hone 3D object completion. Perceptual completion of complex 3D objects may require better pickup and management of perceptual information, to track, encode, and relate multiple edges, surfaces, and volumes (van Lier & Wagemans, 1999; Tse, 2002). At the same time, mental rotation may help infants succeed at complex 3D object completion if their attentional skills are not sufficiently adept (e.g., Colombo, 2001). Thus, young boys—with an advantage in mental rotation—could have an edge, especially considering that stimulus complexity affects mental rotation performance (Shepard & Metzler, 1988). However, once infants can bind local object properties to produce global forms more efficiently (Cohen et al., 2002), these sex differences would diminish.

These mechanisms interact throughout the development of 3D object completion. But this interaction is most apparent between 5 and 7 months of age. Success on a 3D object completion task depends on a tight fit between the complexity of the stimulus, infants' exploratory abilities, and their spatial cognition. Changing any of these factors could mean the difference, for example, between failure to achieve 3D object completion (for a 6-month-old with poor exploratory skill) and robust volume perception (for a 6-month-old boy).

The current study reaffirms the importance of exploring the impact of task demands and stimulus properties on infants' perceptual and cognitive abilities. We discovered an intricate developmental system seeded by multiple processes. These mechanisms play distinct roles in the emergence and refinement of 3D object completion. While research on 3D object completion is still relatively new, similar factors to other types of perceptual completion (Johnson, 2004; Johnson et al., 2003a,b)—stimulus complexity and information pickup—seem to be at play. Changing the task demands changes infants' performance, because how infants make sense of visual stimuli is dependent on their underlying perceptual systems. Our data provide further support for a constructivist view of development (e.g., Johnson, 2010b), wherein children learn how to assemble elements of the visual array into increasingly more complex and sophisticated forms.

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