Published in final edited form as:
Child Dev. 2008 ; 79(5): 1230–1236. doi:10.1111/j.1467-8624.2008.01185.x.

Development of Three-Dimensional Object Completion in Infancy

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Abstract

Three-dimensional (3D) object completion was investigated by habituating 4- and 6-month-old infants (n = 24 total) with a computer-generated wedge stimulus that pivoted 15°, providing only a limited view. Two displays, rotating 360°, were then shown: a complete, solid volume and an incomplete, hollow form composed only of the sides seen during habituation. There were no reliable preferences for either test display by 4-month-olds. At 6 months, infants showed a reliable novelty preference for the incomplete test display. Infants in a control group (n = 24) not habituated to the limited-view wedge preferred neither test display. By 6 months, infants may represent simple objects as complete in 3D space despite a limited perspective. Possible mechanisms of development of 3D object completion are discussed.

Piaget (1954) pioneered the study of infants' perceptual and cognitive abilities with his foundational work on object knowledge and spatial cognition. Since these original studies, a wealth of information on visual-cognitive abilities has accrued in such areas as object permanence (e.g., Baillargeon, 1987; Diamond, 1990), spatial reasoning (e.g., Bremner, 1978; Rieser, 1979), and perceptual completion (e.g., Johnson, Bremner, et al., 2003; Kellman & Spelke, 1983). Departures from the age and motor constraints Piaget suggested originally have been claimed, sparking polemic arguments on the "true" capacities of young infants (Spelke, 1998).

Modern rationalist views of infants' understanding of the physical world have contended that infants are more sophisticated in their representations of the visual world than Piaget surmised (Spelke, Breinlinger, Macomber, & Jacobson, 1992). Studies examining infants' understandings of object continuity and solidity, for example, have suggested that infants as young as 2.5 months may have a rudimentary understanding of object permanence (Aguiar & Baillargeon, 1999). In general, those arguing in favor of the precocious nature of infants' object perception and physical understanding maintain that developmental processes are more related to infants' sensitivity to relevant features of the objects used in the displays rather than changes in the underlying mechanisms of information-processing and object knowledge (e.g., Baillargeon, 2004).

Others have argued for a more gradual emergence of object knowledge over the 1st year after birth—with infants' understanding of the physical world built upon successively more sophisticated attentional skills, an increasing ability to integrate multiple sources of information in the visual array, and emerging manual and other exploratory skills to facilitate the acquisition of physical knowledge (e.g., Colombo, 2001; Gibson, 1988; Johnson, 2003). Work on infants' perception of causality (e.g., Cohen & Oakes, 1993), perception of object

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unity (e.g., Johnson, 2004), and object recognition (e.g., Kraebel & Gerhardstein, 2006) has provided evidence for infants' gradually emerging object knowledge. The present study, therefore, was motivated by this growing awareness of the importance of understanding developmental processes in providing a more accurate account of infants' physical world than is offered by rationalist approaches.

We examined infants' perception of the full, volumetric form of three-dimensional (3D) objects when provided only a limited view, asking if infants represent objects seen from a limited vantage as coherent volumes or instead as consisting solely of the surfaces that are visible from the current viewpoint. This question maps onto work investigating developmental processes of object and spatial knowledge and relates to work on perceptual completion in general in infancy.

The 3D nature of our world may pose a challenge to the immature visual system. Distant objects are often occluded by nearer objects, and recognition of the partially occluded object requires synthesis of the visible portions into a coherent percept. Objects come in and out of existence as they move or observers move around them, and the far sides of opaque objects are blocked from sight by their visible portions—the problem of self-occlusion. Despite the fragmented nature of the visual world, adult observers are adept at discriminating and recognizing complete forms through spatial and spatiotemporal occlusion (Kellman & Shipley, 1991; Marr, 1982) and through self-occlusion (Tse, 2002). Thus, our visual experience is not composed of disjoint surfaces, fleeting percepts of moving objects, and incomplete, hollow volumes; rather, our visual system "fills in" the missing parts, resulting in a richer experience than what is visible directly.

The visual system of the adult is able to accomplish perceptual completion under many circumstances without apparent effort, but the visual experience of very young infants is substantially different. Four-month-olds perceive a moving, center-occluded rod as a unified object rather than two disjoint segments (Kellman & Spelke, 1983), but newborn infants perceive this display as consisting of unconnected pieces (Slater, Johnson, Brown, & Badenoch, 1996). In these investigations, infants were habituated to a display in which a rod moved laterally behind an occluder. After habituation, infants were shown two test displays, both without the occluding box: one depicting a complete, unbroken rod and in the other, two broken rod pieces of the same size as the visible portions seen previously. Consistently longer looking at either test display is interpreted as a novelty response; therefore, a posthabituation preference for the broken rod pieces would imply unity perception during habituation. Newborns preferred the unbroken rod at test, whereas older infants preferred the broken rod parts.

Other experiments examined spatiotemporal completion: the perception of occluded trajectories of moving objects. When shown a display in which a ball moves back and forth, the center portion of its trajectory occluded by a box, infants at 6 months appeared to perceive the ball continuing behind the occluder, both in an habituation experiment (Johnson, Bremner, et al., 2003) and in an oculomotor anticipation paradigm (Johnson, Amso, & Slemmer, 2003), but younger infants provided evidence of perceiving the visible parts of the trajectory only, failing to complete it, in parallel with experiments on perception of object unity described previously. Infants' visual cognition thus undergoes substantial development during the first few months after birth toward an experience of a more holistic percept of the visual environment.

These and other experiments have characterized infants' perception of spatial and spatiotemporal unity. In contrast, little is known about how infants come to understand self-occlusion and perceive volumetric unity. Work on the development of 3D object completion and infants' understanding of self-occlusion may help elucidate how the infant's visual system overcomes the problems imposed on it by the cluttered 3D world as well as further general learning principles.

A subsidiary goal of the present work is to understand better the nature and limits of 3D form perception in young infants. Early research showed that 4-month-olds could discriminate familiar objects in novel axes of rotation from novel rotating objects (Kellman, 1984). Infants in these experiments, however, could not generalize 3D form across views within static displays and required either object or observer movement to discriminate novel and familiar objects (Kellman & Short, 1987). Infants as young as 2 months are adept at picking up 3D structure from kinetic information (Arterberry & Yonas, 2000), and by 4 months, infants are sensitive to some pictorial cues that signify 3D structure (Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Shuwairi, Albert, & Johnson, 2007). Infants at 2 and 4 months will complete a 3D shape when occluded in displays depicting fully rotating 3D forms (Johnson, Cohen, Marks, & Johnson, 2003). Recent work from an operant learning paradigm provides evidence that at 3 months, infants may achieve view-invariant 3D object recognition when given the opportunity to cause the movement of various 3D forms (Kraebel & Gerhardstein, 2006).

Together, this work on perceptual completion and 3D object perception shows that young infants by 4 months show some nascent understanding that objects are continuous in space and that most objects are 3D. Infants appear to continually build upon their existing knowledge and attentional skills to visually complete more complex displays and veridically perceive more complex objects. Still, it is not known when and how infants come to perceive a complete 3D volume through self-occlusion.

In the present experiment, we showed infants computer-generated displays depicting objects rotating in depth around the vertical axis (see Figure 1)—either pivoting back and forth through 15°(*limited view*) or rotating through a full 360°(*full view*). Infants were shown a limited-view display during habituation, providing the opportunity to see only a few faces of the object. Once infants met the habituation criterion, they were shown two new full-view displays. One display depicted a complete solid object, and the other depicted an incomplete hollow object composed of only the surfaces seen during habituation. All the displays contained rich information for 3D form including kinetic cues (e.g., relative motion, contour deformation) and pictorial cues (e.g., shading, line junctions). We reasoned that if an infant perceived the limited-view object as complete during habituation, then during test he or she should respond to the incomplete display as novel and thus look longer at it than at the complete display. If, however, the infant showed no reliable preference for either display following habituation, then we reasoned that infant likely did not perceive the self-occluded surfaces of the limited-view object.

We tested infants at 4 and 6 months to explore developmental differences in performance. To assess whether infants in these age groups show any spontaneous preferences for incomplete or complete 3D objects, infants in a control group were shown complete and incomplete test displays without first being habituated to the limited-view object.

Method

Participants

The final sample consisted of twenty-four 4-month-olds (*M* age = 118.4 days, *SD* = 12.8) with 11 males and 13 females and twenty-four 6-month-olds (*M* age = 179.3 days, *SD* = 9.4) with 12 males and 12 females. Additional infants were observed but excluded from the analyses due to fussiness (9 infants), consistent inattention toward the screen (6 infants), parental interference (2 infants), or experimenter error (2 infants). Participants were recruited via letter and phone using a marketing database containing the names of parents with young children. The majority were from Caucasian, middle-class families in the New York City metropolitan area. All parents were fully debriefed about the experimental procedure and informed consent was obtained before beginning the session.

Apparatus and Stimuli

Infants were tested individually and seated on their parent's lap 120 cm from a 76-cm monitor in a darkened room. An experimenter was hidden behind a divider and operated a Macintosh computer that performed several functions. The computer presented the stimulus displays, stored each infant's data, calculated the habituation criterion for each infant, and changed displays after the criterion was met. The computer also recorded how long each infant looked at each display, according to the experimenter's judgments.

The displays depicted a computer-generated wedge (Figure 1). Each shape subtended a maximum visual angle of 8.5°(height) and 11.5°(width). During habituation, the object rotated 15° back and forth around the vertical axis. It took 4 s to complete a pivot in both directions and return to center. At test, following habituation, the complete object was the simplest interpretation of the limited-view object: a symmetrical mirror of the faces seen originally. The incomplete object was composed of only the faces seen during habituation. In test displays, it took 10 s for the object to make a full rotation. The objects were covered with a brown, wood-like surface and presented against a background consisting of a 12 × 20 grid of white dots, which covered the entire monitor. Informal pilot testing revealed that all the displays were interpreted as rotating 3D objects by adult observers.

Procedure

Each trial began with the presentation of an attention-getter (a looming and contracting ball accompanied by a repetitive sequence of tones) to attract the infant's attention to the screen and center the point of gaze. Once the experimenter determined that the infant had fixated the screen, the attention-getter was replaced with the experimental stimulus and timing of each trial began. A trial ended when the infant looked away for 2 s or until 60 s of total looking had accumulated; the attention-getter was then shown again, immediately followed by a new trial. The habituation display (the limited-view object) was presented until the infant met a habituation criterion: a decline in looking time during four consecutive trials adding up to less than half the total looking time during the first four trials. Upon meeting the criterion, the infant was shown the test displays starting on the next trial. Consequently, there was a minimum of five habituation trials, and the maximum number of trials was set to be 12. The two test displays were seen in alternation three times each—for a total of six posthabituation trials. In the control task, the procedure was the same except infants were not habituated to the limited-view object display first. Instead, infants only saw the two test displays in alternation three times each. Infants were randomly assigned to one of the two test display orders (incomplete first or complete first) and to the habituation task or no-habituation control.

To assure reliability of the experimenter's judgments, an independent observer coded looking times off-line for 25% of the sample. The Pearson correlation between the experimenter's and the coder's judgments of the total looking time on each trial was .93, indicating strong agreement between the on-line and off-line coding.

Results

Data consisted of looking times toward the two displays at test. Before analysis, the data were logarithmically transformed due to excessive skew in some cells that violated the assumptions of the analysis of variance (ANOVA)—data in the figures are based on nontransformed scores.

Preliminary analyses revealed there were no notable differences in looking times based on sex of infant or order of test display presentation, so these factors were not included in further analyses.

Figures 2 and 3 show looking-time results of 4- and 6-month-olds, respectively. A 2 (age: 4 or 6 months) × 2 (condition: habituation or no-habituation control) × 2 (test display: complete or incomplete object) × 3 (test trial block: first, second, or third) mixed-design ANOVA was performed—with age and condition as between-participant factors and test display and test trial block as within-participant factors. The analysis revealed a significant main effect of condition, $F(1, 44) = 16.58$, $p < .001$, partial $\eta^2 = .274$, due to greater looking overall by infants in the control condition; a significant main effect of test display, $F(1, 44) = 25.11$, $p < .001$, partial $\eta^2 = .363$, due to greater looking overall at the incomplete object; and a significant main effect of test trial block, $F(2, 88) = 26.89$, $p < .001$, partial $\eta^2 = .379$, due to an overall decline in looking across test trials. This latter effect was mediated by a reliable Test Trial Block × Condition interaction, $F(2, 88) = 3.83$, $p < .05$, partial $\eta^2 = .08$, stemming from a greater decline in looking across trials by infants in the control condition.

Most important, there was a reliable three-way interaction of age, condition, and test display, $F(1, 44) = 5.11$, $p < .05$, partial $\eta^2 = .104$. Further analyses indicated that this three-way interaction was due to the presence of a significant Condition × Test Display interaction for the 6-month-old infants, $F(1, 22) = 12.00$, $p < .01$, partial $\eta^2 = .353$, but not for the 4-month-old infants, $F(1, 22) = .035$, *ns*, partial $\eta^2 = .002$. Separate pairwise comparisons in the habituation and control conditions revealed that 4-months-olds showed no reliable preference for either test display, $t(11) < 2.2$, $p > .05$ (see Figure 2). Infants at 6 months of age in the control task showed no preference for either test display, $t(11) = 0.836$, *ns*, though 6-month-old infants in the habituation condition reliably preferred the incomplete display, $t(11) = 6.16$, $p < .001$ (see Figure 3).

We conclude that infants at 4 months do not perceive completion of the self-occluded surfaces in limited-view objects. Although previous work has indicated that 4-month-olds may be sensitive to both kinetic and static cues to depth (Arterberry & Yonas, 2000; Bhatt & Bertin, 2001; Kellman, 1984; Shuwairi et al., 2007), infants at this age provide no evidence of sensitivity to the full, volumetric forms of limited-view 3D objects under the conditions we provided. Results of 6-month-olds, in contrast, provide positive evidence for 3D object completion in this age group.

Discussion

We investigated developments in 3D object completion: perception of objects as volumetric and complete in 3D space when only a limited vantage point is available. We habituated infants at 4 and 6 months to displays depicting objects rotating through 15°. During test, infants were shown alternating displays depicting objects, either complete volumes or hollow facades, rotating through 360°. If infants perceived a complete volume with self-occluded surfaces while viewing the limited-vantage object, we reasoned that the incomplete test display should have been experienced as novel and therefore recruit increased looking times relative to the complete display. The 4-month-olds preferred neither test display, providing no evidence for 3D object completion at this age, but 6-month-olds showed reliably longer looking times to the incomplete test display. These older infants provided evidence for perceptual completion of the limited-view stimulus, inferring the existence of self-occluded surfaces. Infants at both 4 and 6 months of age who were not first habituated to the limited-view object showed no reliable preferences for either display—implying that intrinsic preferences for incomplete objects can be excluded as an alternative explanation of infants' performance during the habituation tasks.

Thus, we have evidence for a developmental progression of infants' 3D object completion abilities, strengthening the view that object knowledge emerges gradually over the 1st year after birth. Between 4 and 6 months of age, infants seem to become increasingly proficient at forming percepts of complete volumes. The period around 6 months appears to represent a transitional period in the development of this visual-cognitive skill, as infants' nascent volumetric completion abilities are first becoming evident. Although it is clear that the rudiments of 3D object completion emerge around 6 months of age, further developments in this ability may relate to the complexity of the 3D forms used during testing.

These findings provide evidence regarding the time course of infants' perception of complete forms through self-occlusion to accompany the sizable literature on infants' and adults' perceptual completion abilities (e.g., Johnson, 2004; Kellman & Shipley, 1991; Tse, 2002). More than simply perceiving and registering the visible elements in a scene, perceptual completion through various types of occlusion (Johnson, Bremner, et al., 2003; Kellman & Spelke, 1983) involves the workings of sophisticated and complex mechanisms that fit together the visible parts of the world to form sensible holistic forms. 3D object completion is a perceptual inference that requires infants to recognize the unified and reversible aspects of an object in space.

Understanding the development of 3D object completion in infancy shapes a framework of how object knowledge and perception emerge over the 1st year after birth. Insights into the general processes of development can be gained, as this collective work on visual completion can help inform theories of cognitive development. For example, previous work on infants' visual completion provides strong support for a constructivist view of perceptual development (Johnson, 2003, 2004). Continually more complex forms are derived from the processing of smaller units that are assembled into a fuller percept. The experiments presented here add to this body of knowledge, by showing that 3D object completion perception may be built out of lower perceptual knowledge—kinetic and pictorial information for three dimensionality. Interestingly, infants at around 6 months of age also begin to use similarity of form to organize abstract visual patterns (Quinn, Bhatt, Brush, Grimes, & Sharpnack, 2002). Perhaps bottom-up configural processing, such as grouping by form, is developing in tandem with experiential components, supporting more sophisticated object perception such as volumetric completion.

One possibility is that infants around 6 months, who show the first evidence of 3D object completion, may also be starting to tune into the relevant features of 3D objects during normal visual experience. An object recognition system emerging during the middle of the 1st year (Colombo, 2001) may guide infants' information-processing and attentional allocation. Another possibility builds on Piaget's (1954) proposal that object knowledge is constructed in tandem with the increasing coordination of action systems. The present work on 3D object completion has discovered a perceptual ability whose onset is commensurate with the 5- to 6-month age range during which coordinated visual-manual exploration of objects is known to arise (Eppler, 1995; Rochat, 1989). As they play, infants may discover that objects have hidden surfaces, revealed via rotation, and build up volumetric completion from these explorations.

Acknowledgements

This research was supported by the National Institutes of Health Grant R01-HD40432. Portions of this work were presented at the 2006 meeting of the Vision Sciences Society, Sarasota, FL, and the 2006 International Conference on Infant Studies, Kyoto, Japan. We gratefully acknowledge the infants and parents who participated in the studies. We also thank Juliet Davidow, Melissa Rozon, and Lauren Clepper for their help in recruiting infant participants, and we thank Holly Hamilton and Alissa Gaughan for their assistance with reliability coding.

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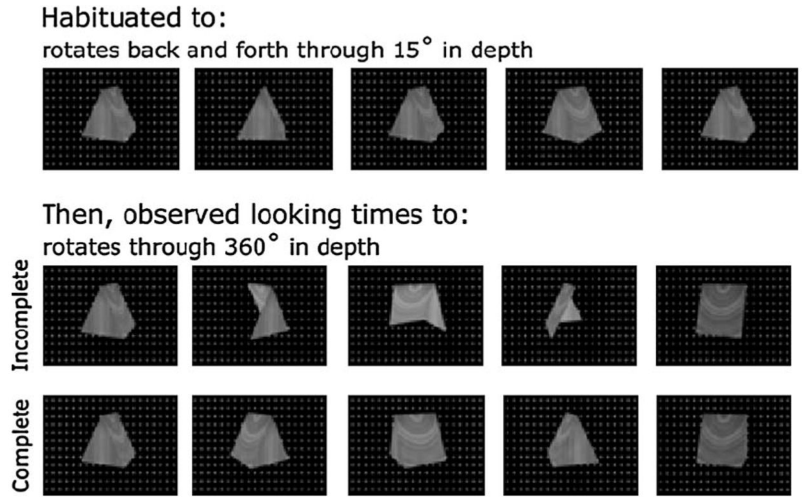

Figure 1. The visual stimulus set

Note. Infants were habituated to a wedge-shaped object that rotated back and forth 15° around the vertical axis. During test, infants viewed a complete and an incomplete version of the object on alternating trials, both rotating through 360°.

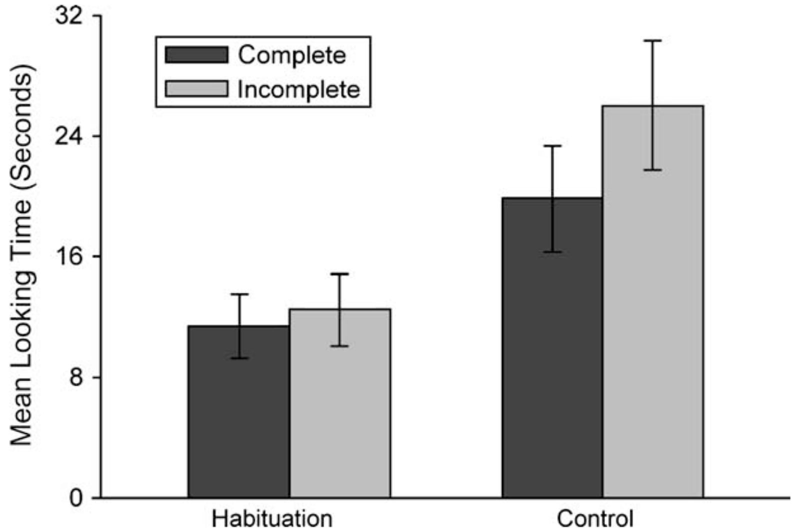

Figure 2. Looking-time results of 4-month-olds

Note. Error bars represent standard error of the means.

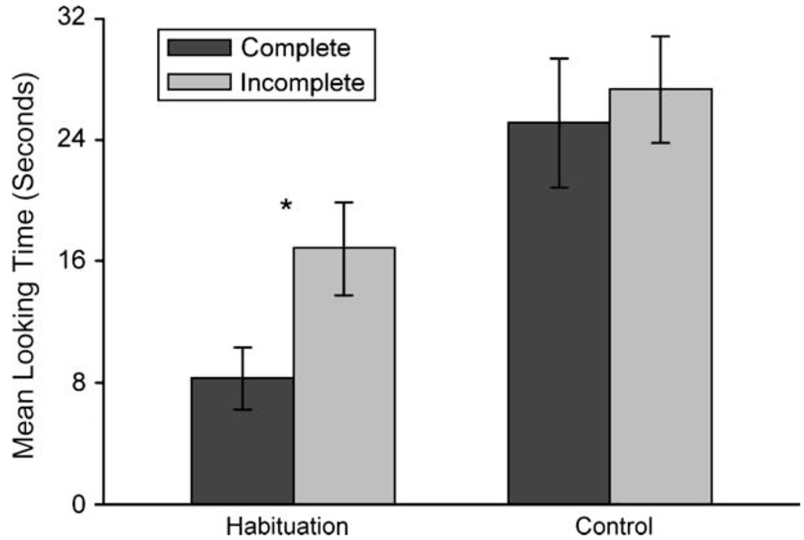

Figure 3. Looking-time results of 6-month-olds

Note. Error bars represent standard error of the means.