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Systems in Development: Motor Skill Acquisition Facilitates Three-Dimensional Object Completion

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How do infants learn to perceive the backs of objects that they see only from a limited viewpoint? Infants' 3-dimensional object completion abilities emerge in conjunction with developing motor skills—independent sitting and visual–manual exploration. Infants at 4.5 to 7.5 months of age ($n = 28$) were habituated to a limited-view object and tested with volumetrically complete and incomplete (hollow) versions of the same object. Parents reported infants' sitting experience, and infants' visual–manual exploration of objects was observed in a structured play session. Infants' self-sitting experience and visual–manual exploratory skills predicted looking at the novel, incomplete object on the habituation task. Further analyses revealed that self-sitting facilitated infants' visual inspection of objects while they manipulated them. The results are framed within a developmental systems approach, wherein infants' sitting skill, multimodal object exploration, and object knowledge are linked in developmental time.

Keywords: perceptual development, three-dimensional object perception, exploration, object manipulation, sitting

Developmental psychology has a long history of linking achievements in infants' motor skills with improvements in perceptual and cognitive abilities. Piaget (1954), for example, proposed that infants' developing motor actions and subsequent exploration of the world are critical for learning and development. Likewise, E. J. Gibson (1988) argued that infants learn about the properties of the world through exploration and that developing motor skills constrain and guide how infants pick up information about objects, surfaces, and events. Piaget viewed motor skill acquisition as a launching point for perceptual and cognitive skills. In contrast, E. J. Gibson took seriously the proposition that motor action, perception, and cognition are linked in real time and throughout development: Perception and cognition remain inextricably grounded in the body and its actions (e.g., E. J. Gibson & Pick, 2000; Thelen & Smith, 1994). The current work was motivated by a developmental systems approach, which emphasizes the developmental processes that facilitate acquisition of new skills, even when the developmental history grows from nonobvious causal factors (e.g., Gottlieb, 2007; Spencer et al., in press). The present study examined how developmental changes in motor skills—sitting and manual exploration—affect three-dimensional (3D) object completion, that is, perceiving an object as a complete volume in visual space despite seeing it only from a limited viewpoint (Soska & Johnson, 2008).

Object Exploration Facilitates Object Perception

Manual exploration provides information about objects in the environment—object properties, such as weight, shape, and surface texture, and affordances for action, such as grasping, banging, sliding, and rolling (Lockman, 2000). Different exploratory procedures yield different types of information (Bushnell & Boudreau, 1993; Lederman & Klatzky, 1987). For example, if infants do not stroke and finger object surfaces independently with their digits, detailed information on object texture may be hard to detect. Older infants with more proficient manual exploration skills are adept at using such exploratory procedures and can extract subtle differences in object properties, but younger infants who cannot yet perform the necessary manual actions show degraded perception of the material properties of objects (Striano & Bushnell, 2005).

With development, object exploration becomes increasingly multimodal, so that concurrent streams of visual, tactile, proprioceptive, and auditory information become available. At first, infants bring objects in their hands straight to their mouths, but by 6 months of age, infants bring objects to their eyes for visual inspection prior to mouthing (Rochat, 1989). Visual exploration becomes coupled with more sophisticated manual actions, such as fingering, rotating, and transferring objects from hand to hand

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(Eppler, 1995). Developmental improvements in multimodal exploration provide a richer source of information about objects. For example, coordinated visual–manual exploration while rotating objects generates kinetic information for depth. Not only do infants see the object moving in depth, they feel themselves turning the object. They therefore receive additional, complementary tactile and proprioceptive information from their hands and arms about the transformations that generate the visual information. Postural control is also implicated in the development of multimodal object exploration. The onset of self-sitting (maintaining balance with the hands freed from supportive functions) is a crucial component in promoting controlled reaching (Rochat, 1992) and eye–hand coordination (Bertenthal & von Hofsten, 1998; Rochat & Goubet, 1995).

Developmental advances in visual–manual object exploration may facilitate object perception and cognition by helping infants to detect the properties and affordances of various objects more readily. In addition, emerging action systems allow infants to learn general properties of the visual world and thereby influence visual attention and cognition. As infants become more adept at object manipulation, they pay more attention to the actions of objects in the world. For instance, in an audiovisual preference task, 5.5-month-olds with higher levels of object manipulation skill matched sounds to object movements more successfully than infants with less proficient exploratory procedures (Eppler, 1995). Experience manipulating objects also facilitates infants' ability to perceive the visual boundaries of objects. Infants who showed longer periods of holding and looking at objects and more frequent switches between looking and mouthing were more likely to distinguish two objects in contact with each other as distinct and segregated in a violation-of-expectation paradigm (Needham, 2000).

Experimental manipulation of infants' object exploration skills provides further evidence that experience handling objects in everyday life facilitates learning general principles about the visual properties of objects. At 3 months, before they could grasp and manually explore objects, the infants were fitted in Velcro *sticky mittens* and encouraged to pick up objects lined with matching Velcro. Those infants with sticky mitten experience showed accelerated object manipulation skills and more interest in objects after the mittens were removed relative to infants in a control group (Needham, Barrett, & Peterman, 2002). Early experience with object exploration also influenced 3-month-olds' perceptions of other people's actions with objects (Sommerville, Woodward, & Needham, 2005). Relative to controls, infants with sticky mitten experience showed more sensitivity to an actor's goal of reaching for a particular object in a visual habituation paradigm.

Learning to Perceive Objects as 3D

A central property of objects is that they are 3D. However, 3D objects present a problem for the visual system because people can see objects only from a limited viewpoint at any given moment. Thus, the far sides of objects are occluded by the visible portions. Nonetheless, adults automatically perceive objects as volumes in 3D space. They fill in the nonvisible surfaces to perceive solid volumes, not hollow facades (Tse, 1999). Perceiving the unseen backs of objects is critical for recognizing objects and analyzing scenes, and accurate perception of object size and form is necessary for planning motor actions. Grasping objects and navigating around obstacles involves judging the extent of their boundaries, including the boundaries on the far sides of objects, which are not directly accessible to the visual system from any single viewpoint.

Researchers have described the extent of adults' 3D object completion abilities (Tse, 2002), and related work on viewpoint-invariant object perception has revealed aspects of the perceptual processing involved in recognizing objects in the 3D world (Palmeri & Gauthier, 2004). In contrast, the 3D object completion abilities of young infants remain poorly characterized, and little is known about how this critical perceptual ability develops. Presumably, 3D object completion has roots in the ability to perceive two-dimensional objects as visually complete through occlusion (Johnson, 2004; Johnson, Bremner, Slater, & Mason, 2003). By 4 months of age, infants are sensitive to kinetic and pictorial cues to 3D shape (Arterberry & Yonas, 2000; Bhatt & Bertin, 2001; Kellman & Short, 1987). However, perceptual sensitivity to 3D shape does not guarantee the ability to infer the 3D form of the back of an object. Perceiving objects as complete, enclosed solids appears to develop later.

Recent research indicates that infants' 3D object completion abilities emerge during the middle of the first year after birth (Soska & Johnson, 2008). Four- and 6-month-old infants were habituated to visual displays of computer-generated objects that provided only a limited view as the objects pivoted 15° around the vertical axis. At test, on alternating trials, infants viewed displays of solid, complete objects and hollow, incomplete objects (with only the sides seen in the limited view) that now rotated a full 360° in depth. Four-month-olds looked equally long at the two test displays, suggesting that they were not sensitive to the self-occluded surfaces of the 3D form seen during habituation. Six-month-olds, in contrast, looked reliably longer at the incomplete test display, implying perception of a complete form during habituation. The findings point to an important developmental transition in infants' perceptual completion of 3D form between 4 and 6 months of age, but the developmental processes that support perception of the self-occluded backs of objects have yet to be uncovered.

Current Study

The current study used a developmental systems approach to examine how infants acquire 3D object completion. We began with the hypothesis that developmental changes in infants' motor skills might underlie the ability to perceive the unseen backs of objects. Two types of developmental changes seemed likely candidates: improvements in self-sitting ability and coordinated visual–manual object exploration. Between 4 and 6 months, most infants acquire the ability to sit independently, freeing the hands for play and promoting gaze stabilization during manual actions (Rochat & Goubet, 1995). Thus, self-sitting ability might spur improvements in coordinating object manipulation with visual inspection. Turning objects over, fingering objects, and transferring objects to look at and feel their backs are easily reproducible actions that would promote learning about 3D objects' forms. Rotating toys while looking at them brings the back side of the object into view. Fingering toys—running the fingers over the surface—while visually examining them would provide infants with visual and tactile information about object form and contour.

Looking at objects while transferring them between hands would provide infants with multiple views of objects.

To ensure coverage of the entire period of rapid improvements in object manipulation skill and self-sitting, we tested infants between 4.5 and 7.5 months of age. Infants participated in a replication of the visual habituation paradigm used by Soska and Johnson (2008). As in the earlier study, we considered posthabituation looking preferences for the display of the hollow, incomplete object to be evidence that infants had perceived a complete 3D object during the habituation period. We also assessed infants' manual exploration skills by observing their spontaneous object manipulation, and we obtained retrospective parental reports of the duration of infants' sitting experience. We expected that infants who showed greater capacity to explore objects from multiple viewpoints would also have had more opportunities to learn about objects' 3D forms. Thus, individual differences in object exploration should predict individual differences in object perception, in particular 3D object completion. Specifically, we expected that coordinated visual–manual exploration (rotations, fingerings, and transfers with looking at toys) and self-sitting experience would predict infants' looking preferences for the complete and incomplete object displays.

We expected that age at testing would not be a reliable predictor of 3D object completion after controlling for more specific, experience-related changes. Age is a stand-in for other time-related factors, such as possible maturational components and general visual experience, which would not uniquely predict 3D object completion. Tripod-sitting experience, that is, sitting while using the hands for support, is a precursor of self-sitting but does not permit unhampered manual exploration. Experience with tripod sitting would not be expected to predict 3D object completion but could be used to control for total duration of sitting experience. Likewise, holding skill (represented by the number of toy drops) reflects general manual skill that doesn't directly allow the exploration of objects from multiple viewpoints. Simply holding an object does not provide sufficient visual–haptic information to learn about its form. Manual exploration without looking (rotations, fingerings, and transfers without looking at toys), likewise, should not predict 3D object completion, because this type of exploration provides only tactile information during manipulation. Corroborating visual information about object form is also needed to generate long-lasting changes in visual perception.

Method

Participants

Families were recruited through visits to nearby hospitals and brochures sent to parents with young children whose names were obtained through a commercial database. Most families were Caucasian, middle class, and lived in the New York City metropolitan area. All infants were healthy and born at term. As compensation, infants received a small toy or baby shirt.

The final sample consisted of 28 infants (13 boys, 15 girls) who contributed data to both the manual skill and visual habituation procedures. Their ages ranged from 4.70 to 7.43 months ($M = 6.00$ months). Data from an additional 19 infants were not included because they did not complete the visual habituation procedure (4 infants) or the manual skill assessment (9 infants) or because of parental interference (2 infants), equipment failure (2 infants), or experimenter error (2 infants). Whether infants participated in the manual skill assessment or the visual habituation task first was counterbalanced across the sample.

An experimenter observed infants' sitting ability by encouraging them to sit on the floor while holding an object. Of the infants, 14 could not sit without help from a caregiver, 4 could support themselves in a tripod position (propped on their hands for balance), and 10 could self-sit independently (without using their hands for balance). In a structured interview, parents retrospectively reported infants' sitting experience, using baby books or calendars to aid their memory (see Adolph, 2002). We defined the onset of tripod sitting as the first day when parents saw infants sit on the floor for at least 30 s, maintaining balance by placing their hands on the floor between their outstretched legs, and we defined the onset of independent self-sitting as the first day when infants maintained balance for at least 30 s without using their hands. Experience with tripod sitting ranged from 7 to 44 days ($M = 19.1$ days), and experience with self-sitting ranged from 15 to 57 days ($M = 34.3$ days). Laboratory assessments of sitting ability matched parents' reports: No parents said that their infants could self-sit or tripod sit if the infants could not.

Manual Skill Assessment

Caregivers held infants in an upright sitting position on the floor while an experimenter offered infants 4 toys from a set of 12 to explore one at a time for one trial each. Because some infants could not yet sit independently, all caregivers were encouraged to hold and support their infants during the manual skill assessment. Toys were between 7 cm and 10 cm wide, could easily fit into infants' hands, and were readily graspable (Figure 1). They were made of plastic, wood, and spongy materials and had colorful patterns on the front and back. The selection of toys for each infant

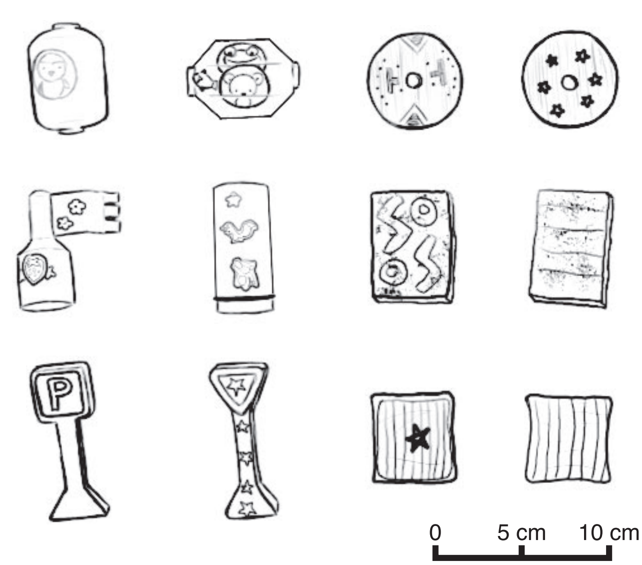

Figure 1. Toys offered to infants for exploration during the manual skills assessment.

and the order in which they were offered was counterbalanced across the sample.

Each of the four toy trials began with the experimenter presenting the toy at midline. If infants did not grasp and hold the toy within 10 s, the experimenter placed it into their hands and helped them to grasp it. Of the 112 trials in the data set, 9 began with the experimenter placing the toy into infants' hands. Trials lasted from the moment when infants grasped the toy until they had accumulated 60 s of spontaneous manual exploration. If infants dropped the toy and did not recover it within 5 s (or it rolled outside of their recoverable range), the experimenter offered it to them again or placed it into their hands. After 60 s of accumulated play, the experimenter removed the toy from infants' hands and offered the next toy. All trials were recorded with a digital video camera situated to provide a head-on view of infants' activity and angled downward to capture infants' body position, eyes, and hands as they explored the toys.

A primary coder (Kasey C. Soska) scored the object manipulation data, using computerized video-coding software, MacSHAPA (www.openshapa.org), to record the frequencies and durations of infants' actions (Sanderson et al., 1994). Holding skill was quantified by the number of times infants dropped toys. The coder scored three measures of manual exploration without looking: the number of times infants rotated objects (at least 90°), fingered objects (by moving the fingers over the surface), and transferred objects between hands (with less than 5 s of both hands holding and no concurrent mouthing) without looking at the object. He scored three parallel measures of coordinated visual–manual exploration: the number of times infants rotated, fingered, and transferred objects between hands while looking at the object for at least 0.5 s. A second coder scored 25% of each infant's data to verify the reliability of the codes. Correlations between primary and reliability coders for duration of looking and frequency of drops, rotations, fingerings, and transfers ranged from .85 to .98.

Visual Habituation

Infants viewed displays of computer-generated, wedge-shaped objects (see Figure 2 for a sketch of the stimuli) identical to those used by Soska and Johnson (2008). Each shape subtended a maximum visual angle of 8.5° (height) and 11.5° (width). The objects in all displays were presented against a 12 cm × 20 cm grid of white background dots and were rendered with the appearance of a brown, wood-like surface. In the habituation phase, the object was presented with a limited view (Figure 2A): It rotated around the vertical axis 15° left and right in depth, requiring 2 s to complete a pivot in both directions and return to center. During the test trials, the complete object view (Figure 2B) was a symmetrical mirroring of the faces seen in the limited view. The incomplete object view (Figure 2C) was a hollow form, composed of only the two faces seen during habituation. It took 4 s for the objects to complete a full rotation in both test displays.

Infants viewed the displays while seated on a parent's lap 120 cm away from a 76-cm monitor in a darkened room. A trained experimenter (Kasey C. Soska), who was unable to see the stimuli being presented, was hidden behind a divider and could see only the infants' faces on a monitor. The experimenter operated a Macintosh computer using Habit software (Cohen, Atkinson, & Chaput, 2000) that presented the stimulus displays and recorded infants' looking at the displays, according to the experimenter's judgments.

An attention getter (a looming and contracting ball accompanied by a sequence of tones) was used to orient infants to the center of the monitor at the beginning of each trial. When the experimenter determined that infants were looking at the screen, he presented the display and began timing the trial. Trials ended when infants looked away for 2 s or when the display was on screen for 60 s. During habituation, the limited-view display was presented until infants' accumulated looking time during 4 consecutive trials was less than half the summed looking times of the first 4 trials. Thus,

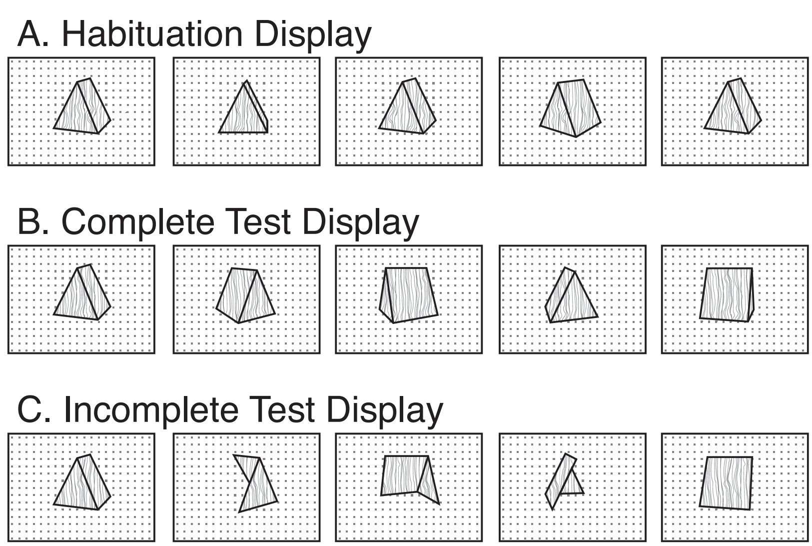

Figure 2. Sketch of computer-generated displays used during visual habituation. (A) The habituation display was a wedge-shaped object pivoting 15° in depth. (B) The complete test display was a symmetric interpretation of the habituation display rotating 360° in depth. (C) The incomplete test display was a hollow form composed only of the surfaces seen during habituation, which also rotated 360° in depth.

infants saw the habituation display for a minimum of 5 trials. If they did not meet the criterion after 12 trials, the experimenter presented the test displays anyway. Infants viewed the two test displays in alternation three times each, with the order of the displays counterbalanced across the sample. The reliability of the experimenter's on-line judgments of looking times was assessed by comparing his judgments with those of a second coder who scored data from 25% of the sample from videotapes. The correlation between the two observers' judgments was .98 for total looking time per trial.

Results

Infants' looking times for the incomplete and complete test displays were summed, and the proportion of looking toward the incomplete display relative to total looking was calculated for each infant. As seen in Figure 3A, the average proportion of looking was 52.7% and ranged from 77.8% (a strong preference for the incomplete display) to 29.8% (a strong preference for the complete display). Further analyses were geared toward assessing the effects of motor skill and exploration on looking preferences.

Influences of Motor Skill and Visual–Manual Exploration on Infants' Looking Preferences

We examined several potential predictors of infants' posthabituation looking preferences: age at testing, tripod and self-sitting experience, holding skill, measures of manual exploration without looking, and measures of coordinated visual–manual exploration. We assumed that greater sitting skill would be associated with more days of tripod and self-sitting experience and that higher levels of manual skill would be associated with fewer drops and more frequent bouts of rotations, fingerings, and transfers, especially while looking at the objects.

Infants displayed a wide range of scores for posthabituation looking preference (Figure 3A) and for each of the potential predictors (Figures 3B–3F). Notably, 2 infants never dropped toys, and 9 infants never transferred objects between hands (with or without looking). Every infant rotated and fingered objects at least once, either while looking or while not looking.

Table 1 shows the zero-order correlations among predictor variables and with the proportion of looking at the incomplete display. Looking preferences were reliably predicted by sitting experience (for both tripod and self-sitting) and coordinated visual–manual exploration (including bouts of rotations, fingerings, and transfers), $rs(27) \geq .40$, $ps < .05$. Infants' age, holding skill, and—most important—measures of manual exploration without looking were not significantly related to posthabituation looking preferences. Independent-sitting experience was related to several predictor variables: Infants with more self-sitting experience tended to be older, had more tripod-sitting experience, and produced more rotations and transfers while looking, $rs(27) \geq .40$, $ps < .05$. Measures of coordinated visual–manual exploration were highly

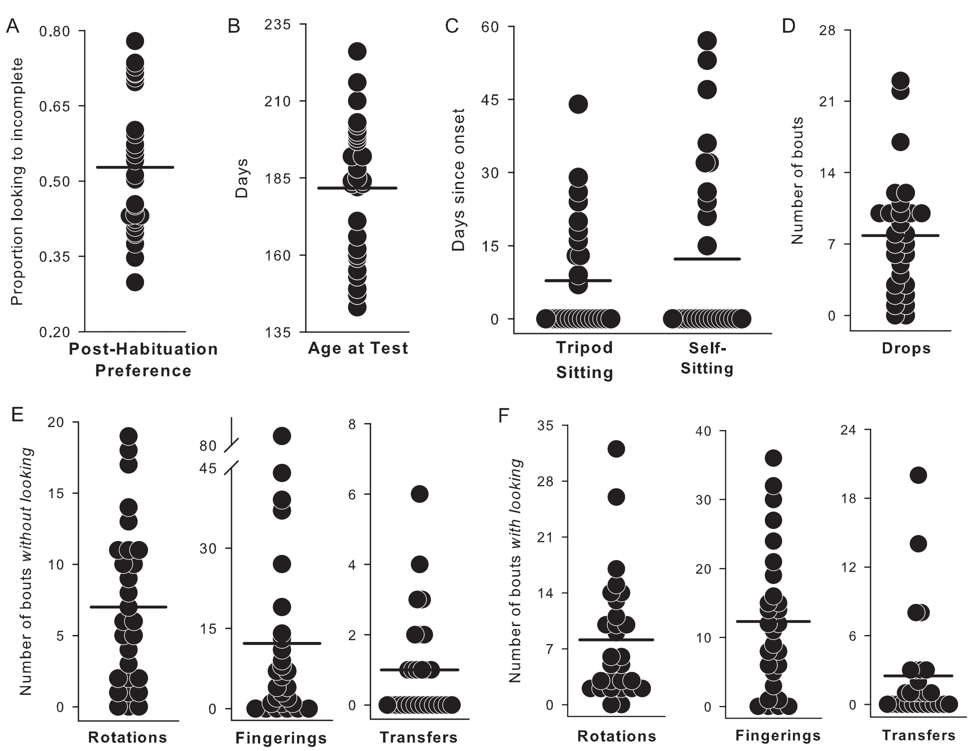

Figure 3. Individual infants' contributions to each predictor variable. Mean values are represented by horizontal lines on each plot. (A) Posthabituation looking preferences toward the incomplete object display. (B) Infants' ages at testing in days. (C) Days of tripod and self-sitting experience. (D) Number of drops of toys during play. (E) Number of bouts of rotations, fingerings, and transfers without looking at toys during play. (F) Number of bouts of rotations, fingerings, and transfers with looking at the toys during play.

Table 1
Correlations Between Infants' Posthabituation Looking Preferences, Age at Test, Tripod and Self-Sitting Experience, Holding Skill (Drops), Manual Exploration Without Looking, and Coordinated Visual–Manual Exploration

		Predictor variables									
						Without looking			With looking		
Variable	Looking preference	Age	Tripod sitting experience	Self-sitting experience	Drops	Rotations	Fingerings	Transfers	Rotations	Fingerings	Transfers
Age	.19	—									
Tripod-sitting experience	.41*	.33	—								
Self-sitting experience	.51**	.55**	.50**	—							
Drops	.18	−.15	.13	.18	—						
Without looking											
Rotations	−.08	.09	.01	.04	.29	—					
Fingerings	−.22	−.10	.10	−.24	.03	.17	—				
Transfers	.01	−.04	−.31	−.01	−.10	.06	.06	—			
With looking											
Rotations	.45*	.36	.20	.49**	−.08	.14	.10	.51**	—		
Fingerings	.40*	.23	−.03	.25	.29	.36	.11	.37	.50**	—	
Transfers	.53**	.23	.11	.40*	−.19	−.06	−.08	.45*	.85**	.29	—

* $p < .05$. ** $p < .01$.

intercorrelated: Infants who produced more rotations while looking tended to produce higher frequencies of fingerings and transfers while looking, $rs(27) \geq .50$, $ps < .01$. Rotations and transfers while looking were correlated with the same manual actions without looking, $rs(27) \geq .40$, $ps < .05$.

Because age, sitting experience, and manual exploration skills were intercorrelated, we used a hierarchical linear regression analysis to examine the unique contributions of these variables for explaining posthabituation looking preferences. The general strategy for this analysis was to enter each variable or block of variables into the regression equation one at a time to observe their individual effects on R^2, a measure of between-infant variation in proportion of looking at the incomplete test display. As each block was entered into the regression, the contributions of previously entered predictors were partialed out, allowing the unique contribution of each subsequent set of variables to be observed. The blocks were ordered to assess the effects of sitting experience and manual exploration skills while controlling for chronological age and to observe the effects of manual exploration skills while controlling for sitting experience. Within the general categories of sitting experience and manual exploration, we entered nuisance variables in earlier blocks to control for their influence in later blocks. Thus, chronological age was entered first. Next, the sitting predictors were entered—with the nuisance variable, tripod-sitting experience, entered before self-sitting experience. Holding skill and manual exploration without looking were also considered to be nuisance variables; we entered these factors before entering coordinated visual–manual exploration in the final block.

Table 2 shows the change in R^2 as each block of predictors was entered. In the first block, age at testing explained only 3.5% of the variance and was not a significant predictor. Likewise, in the second block, tripod-sitting experience did not explain a significant amount of unique, additional variance (13.2%). In the third block, after controlling for effects of age and tripod-sitting experience, independent-sitting experience explained an additional 13.6% of variance in infants' looking preferences—a significant contribution. Holding skill was entered next but explained only 0.2% of unique variance. Manual exploration without looking explained only an additional 4.8% of variance in looking preferences. In the final block, after partialing out the effects of all previously entered predictors, coordinated visual–manual exploration accounted for an additional 29.3% of the variance. With all of the variables entered into the model, these predictors were able to account for 64.6% of the variability in infants' proportion of looking at the posthabituation display, $F(10, 27) = 3.10$, $p < .05$.

The regression analysis showed that both self-sitting experience and coordinated visual–manual exploration were significant predictors of infants' looking preferences. To assess the independent effects of self-sitting after controlling for visual–manual exploration, we tested a second regression model in which self-sitting experience was entered in the final block rather than the third block. Age at testing, tripod-sitting experience, holding skill, and manual exploration without looking were entered in the first four blocks; as before, none of these factors could account for signifi-

Table 2
Hierarchical Regression With Age, Tripod- and Self-Sitting Experience, Holding Skill (Drops), Manual Exploration (Bouts of Rotations, Fingerings, and Transfers) Without Looking, and Coordinated Visual–Manual Exploration (Bouts of Rotations, Fingerings, and Transfers) With Looking on Infants' Posthabituation Looking Preferences

Predictor	R^2	R^2 change
Age at testing	.035	—
Tripod-sitting experience	.167	.132
Self-sitting experience	.304	.136*
Holding skill	.306	.002
Manual exploration without looking	.353	.047
Coordinated visual–manual exploration	.646	.293*
Final model	$F(10, 27) = 3.10^*$	

* $p < .05$.

cant variance in looking preferences (all changes in $R^2 < 13.3\%$, $ps > .05$). Coordinated visual–manual exploration—entered as the penultimate, fifth block—still explained unique, additional variance, controlling for the previously entered variables (change in $R^2 = 34.2\%$, $p < .01$). Entered as the last block, self-sitting experience explained only 0.6% of unique variance, and the change in R^2 was not significant. In summary, independent-sitting experience does not appear to have unique predictive value, because it was able to predict infants' novelty preference scores only when visual–manual exploration was not previously controlled. Coordinated visual–manual exploration, on the other hand, was a robust and powerful predictor of posthabituation looking preferences.

Comparison of Visual–Manual Actions by Sitting Ability

The regression analyses suggested that one route toward 3D object completion might stem from the development of self-sitting and subsequent increases in visual–manual exploration as infants' hands are freed from supporting functions. We used an analysis of covariance to assess the effects of self-sitting on the frequency of manual exploration with and without accompanying visual inspection. The analysis compared the number of rotations, fingerings, and transfers with and without looking for non-sitters (including tripod sitters and infants with no sitting experience) and self-sitters. We considered tripod sitting to be a nuisance variable because it was correlated only with self-sitting, not with manual exploration (see Table 1). Thus, to assess the unique effect of self-sitting, we treated tripod sitting as a covariate—equating all participants on the mean days of tripod-sitting experience for the sample.

As shown in Figure 4, infants performed more rotations and fingerings than transfers (note differences in scale on graphs). In addition, self-sitters produced more coordinated visual–manual exploration than manual exploration without looking, but non-sitters produced equal amounts of manual exploration with and without looking. A 3 (manual exploration: rotations, fingerings, transfers) × 2 (visual inspection: with looking, without looking) × 2 (sitting skill: nonsitter, self-sitter) mixed-design analysis of covariance with tripod-sitting experience as a covariate confirmed a main effect of manual exploration, $F(1.2, 29.87) = 6.60$, $p < .05$, partial $\eta^2 = .21$. (Because sphericity could not be assumed for manual exploration and its interactions, all F tests with this variable have been Greenhouse–Geisser corrected.) Post hoc, Sidak-corrected pairwise comparisons showed that infants performed more rotations ($M = 15.11$, $SD = 10.27$) and fingerings ($M = 24.42$, $SD = 22.20$) than transfers ($M = 3.50$, $SD = 5.52$), $ps < .01$, but performed similar numbers of rotations and fingerings, $p > .05$.

The analysis also confirmed a significant interaction between visual inspection and sitting skill, $F(1, 25) = 7.90$, $p < .01$, partial $\eta^2 = .24$. Follow-up, Sidak-corrected pairwise comparisons within each sitting group revealed equal amounts of manual exploration with and without looking in non-sitters, $p > .05$, but more manual exploration with looking than without in independent sitters, $p < .01$. This finding is reflected in Figure 4 by the relative heights of the bars for each sitting group. We found no effects for the covariate, tripod-sitting experience.

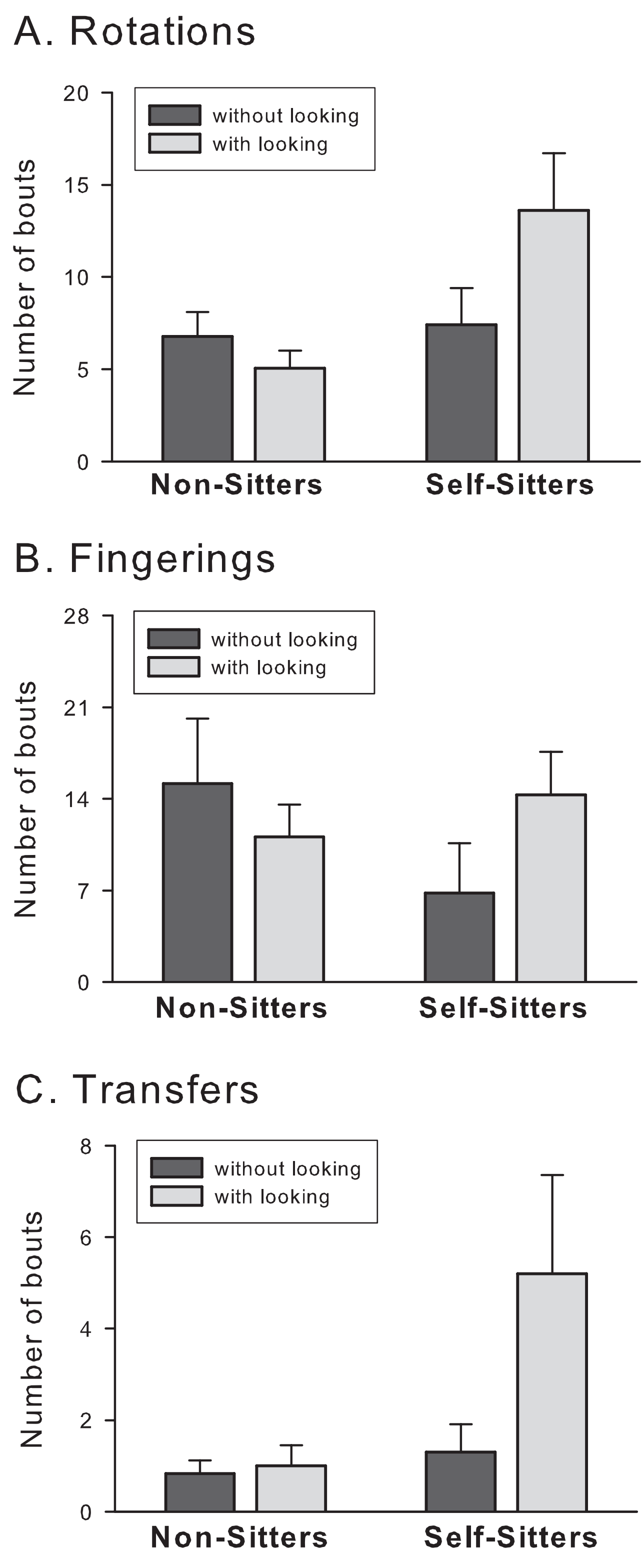

Figure 4. Mean number of bouts (with and without looking at the toys) of (A) rotations, (B) fingering, and (C) transfers during the structured play session grouped by infants' independent self-sitting ability. Self-sitters manipulated objects more frequently while they were looking at them than when they were not looking at them, but non-sitters manipulated objects equally often while looking and not looking at them. Error bars represent standard errors of the mean.

Discussion

Exploring the world and learning about the world are inextricably linked (E. J. Gibson, 1988). Inspired by a developmental systems approach (Gottlieb, 2007), the present study showed how developmental changes in visual–manual exploration drive developmental changes in perceptual completion of 3D object form. Previous work (Soska & Johnson, 2008) identified an age-related change in infants' 3D object completion abilities, from nonperceivers in a 4-month-old age group to perceivers in a 6-month-old group. Here, we used the same visual habituation task to assess individual differences in the ability of 4.5- to 7.5-month-old infants to perceive the back sides of 3D objects seen from a limited viewpoint. We also observed the same infants during spontaneous object exploration and obtained parents' reports of infants' sitting experience. By sampling across the entire age range, we found a gradient of looking preferences for the posthabituation display of the incomplete object—the index of whether infants had perceived a complete 3D form during the habituation period. We also found a correspondingly large range in manual exploration abilities and sitting experience.

Self-sitting experience and coordinated visual–manual exploration were the strongest predictors of performance on the visual habituation task. However, self-sitting had explanatory power only because of its connection to infants' visual–manual exploration. Self-sitting infants performed more manual exploration while looking at objects than did non-sitters. Visual–manual object exploration is precisely the skill that provides active experience with viewing objects from multiple viewpoints, thereby facilitating perceptual completion of 3D form.

Action Origins of Object Perception

In principle, infants might derive 3D object completion from visual transformations generated by others. For example, as other people move objects or as infants are moved around objects, early visual abilities might support the acquisition of 3D object completion. By 5 months of age, infants are adept at recognizing objects across changes in viewpoint (Kellman & Short, 1987; Kraebel & Gerhardstein, 2006), perceiving object movements and shape across occlusion (Hespos & Rochat, 1997; Johnson, 2004; Johnson, Bremner, Slater, & Mason, 2003), and using various sources of information to perceive 3D shape (Arterberry & Yonas, 1988; Bhatt & Bertin, 2001; Yonas, Arterberry, & Granrud, 1987). A developing object recognition system (Colombo, 2001) could guide infants' visual inspection of objects toward the relevant features of 3D objects. In this hypothetical account, because older infants have had more experience viewing objects, they might show stronger evidence of 3D object completion. In the current study, however, age at testing (a stand-in for general visual experience and maturation) did not predict 3D object completion.

An alternative hypothesis—and a guiding hypothesis for the current study—was that visual experience alone is insufficient to spur learning about 3D object form. Active visual–manual exploration provides information about infants' own role in controlling an event while simultaneously generating multimodal information for the perceptual systems. Object recognition in adults is greatly enhanced when observers actively control the change in object viewpoint (Simons, Wang, & Roddenberry, 2002; Wexler, 2002). However, in learning to perceive objects' backs, only certain kinds of active exploration are beneficial. Holding skill and rotating, fingering, and transferring objects without simultaneously looking at them did not predict perceptual completion abilities. Coordinating visual inspection with manual exploration is critical. In principle, several ways of visually and manually exploring objects, such as a looking at their fronts while holding their backs, could allow infants to pick up information on 3D object form. Yet, our data show that only the visual–manual skills involved in generating changes in object viewpoint—rotating, fingering, and transferring while looking—were related to 3D object completion.

To learn about objects' backs, infants have to manipulate objects to actively generate continuous visual transformations, but how much experience do infants actually need and get? Opportunities for learning about objects through visual–manual exploration are immense. In the mere 4 min of our laboratory assessment, infants displayed a vast capacity for exploratory play. One infant fingered the toys 82 times (see Figure 3E), and another transferred the toys 20 times (see Figure 3F), roughly every 12 s. Presumably, opportunities for learning during everyday play outside the laboratory must balloon to tremendous amounts. Estimates of daily activity in other domains support such a proposal. In a single day, infants may produce over 50,000 eye movements (Johnson, Amso, & Slemmer, 2003), take nearly 15,000 walking steps (Adolph, Badaly, Garciaguirre, & Sotsky, 2008), and hear as many as 2,100 words (Hart & Risley, 1995, p. 132).

Given sufficient experience to support learning, there is room for individual differences in object exploration styles. Some infants produced primarily rotations over the other visual–manual actions, and others produced primarily fingerings over the other actions.[1] Exploration style, however, was not related to posthabituation looking preferences. All of these exploratory actions provide visual–haptic information about objects' contours and shape. It may be that only the overall amount of visual–manual exploration is necessary for learning about the backs of objects, given infants' immense experience with exploring objects.

What drives infants to explore and learn about 3D object form? Infants' actions are not performed mindlessly or reactively (von Hofsten, 2004). Presumably infants explore objects to learn about their functional properties (E. J. Gibson, 1988). Perceptual learning throughout early infancy is attuned to affordances—the possibilities for action—whether during locomotion, manual exploration, or oral exploration (Adolph, Eppler, Marin, Weise, & Clearfield, 2000; Bourgeois, Khawar, Neal, & Lockman, 2005; Rochat, 1987). As infants are discovering the functional uses of objects, they are also learning about their physical properties (Bushnell & Boudreau, 1993). One salient feature of most objects is that they have backs. Knowing that objects have backs is important for infants to plan effective grasping and exploration. Therefore, infants' perception of object properties and how infants functionally use object properties are coupled during real time play

[1] Exploration style was identified with a hierarchical cluster analysis (with Euclidian distance and between-group linkage) on the total number of bouts of rotating, fingering, and transferring. The groups identified with the hierarchical analysis were verified with a K means cluster analysis constrained to two clusters—agreement between the two methods was high ($\kappa = .92$, $p < .001$).

(Ruff, 1986). Our findings lend support to the developmental links between infants' motor skills and cognition. Research supporting this claim has played out in several domains, including the link between object exploration and action understanding (Sommerville et al., 2005) and independent locomotion and spatial cognition (Campos et al., 2000).

Postural Basis for Object Exploration

If visual–manual exploration leads to 3D object completion, what are the developmental origins of visual–manual exploration? Of course, less sophisticated forms of object exploration (manipulation without coordinated visual inspection) precede the more sophisticated exploratory procedures, but where then do less sophisticated forms come from? Reed (1982) and others have argued for the primacy of posture. Accordingly, we found that self-sitting ability promoted coupling between visual inspection and object manipulation. The ability to hold an object with one hand and finger it with the other, the ability to transfer an object from hand to hand, and so on require infants to stabilize their trunks so that their arms and heads are free to move. As infants achieve upright self-sitting, the hands are freed from supporting functions, and gaze is more easily stabilized during reaching (Bertenthal & von Hofsten, 1998; Rochat & Goubet, 1995). Infants given early experiences with postural control or object engagement at 4 months showed advanced onset of reaching (Lobo & Galloway, 2008). Moreover, these infants showed more haptic exploration of objects a few weeks later and displayed more means–end behaviors.

Self-sitting ability, coordinated visual–manual exploration, and 3D object completion are part of an integrated developmental system. Whereas active, self-initiated visual–manual exploration appears to be critical to the development of 3D object completion, self-sitting is only developmentally linked to object completion because it facilitates visual–manual exploration. In our study, infants displayed coordinated visual–manual exploration or its absence relative to sitting proficiency even though caregivers helped support infants during the manual skills assessment. In other words, infants brought to the structured play session their repertoires of exploration from outside the lab. The development of coupled visual–manual exploration is dependent on everyday experience sitting up and playing with toys in the home.

The ability to self-sit confers more opportunities for infants to acquire visual–manual exploratory skill. Caregivers might be able to accelerate the acquisition of coordinated visual–manual exploration by artificially enhancing postural control (Lobo & Galloway, 2008) or providing early object engagement experiences (Needham et al., 2002), but unless these interventions are part of an experimental manipulation or are normal rearing practices in the culture (e.g., Bril & Sabatier, 1986), it seems unlikely that caregivers provide enough supported sitting experiences. Although it is possible that other hands-free postures, such as playing while supine or in a prone position, could support the development of visual–manual exploration, the strong connection between the acquisition of self-sitting and visual–manual exploration argues against this possibility. Apparently, infants have to learn to sit up on their own to have diverse and distributed experiences exploring objects.

Conclusions: Systems in Development

We examined the developmental link between motor skill acquisition and 3D object completion. Maturation and unimodal visual experience (represented by chronological age) do not predict these perceptual abilities. Rather, 3D object completion is rooted in the development of exploratory skill. Infants may first develop the ability to visually and manually explore objects to reveal their backs, and as they play, they build up what they know about objects from this exploration. However, the development of 3D object completion may not be this simple and linear: Perception and action are not dissociable developmental agents. Every time infants explore objects, their perceptual and motor abilities influence their exploratory behaviors. Thus, emerging perceptual abilities guide object exploration, and simultaneously, perception becomes elaborated with the acquisition of new motor skills. As J. J. Gibson (1979) put it, the primary role of perception is to guide action; motor actions, in turn, provide new information for perceptual systems. Moreover, the developmental history of a new skill can have a surprisingly twisted and nonobvious path. The current study suggests that the emergence of 3D object completion arises in a developmental cascade from postural coordination to object exploration to perception and cognition.

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