

The development of depth perception from motion parallax in infancy

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Little is known about infants' perception of depth from motion parallax, even though it is known that infants are sensitive both to motion and to depth-from-motion cues at an early age. The present experiment assesses whether infants are sensitive to the unambiguous depth specified by motion parallax and, if so, when this sensitivity first develops. Eleven infants were followed longitudinally from 8 to 29 weeks. Infants monocularly viewed a translating Rogers and Graham (1979) random-dot stimulus, which appears as a corrugated surface to adult observers. Using the infant-control habituation paradigm, looking time was recorded for each 10-sec trial until habituation, followed by two test trials: one using a depth-reversed and one using a flat stimulus. Dishabituation results indicate that infants may be sensitive to unambiguous depth from motion parallax by 16 weeks of age. Implications for the developmental sequence of depth from motion, stereopsis, and eye movements are discussed.

Infants, like adults, make use of a number of monocular, binocular, static, and kinetic cues to help them perceive their 3-D visual environment. It appears that infants' sensitivity to these cues develops in an orderly fashion. Five- to 7-month-olds use a variety of monocular "pictorial" cues to perceive shape and depth, including relative size (Yonas, Granrud, & Pettersen, 1985), shading (Granrud, Yonas, & Opland, 1985), and interposition (Granrud & Yonas, 1984). Infants are sensitive to kinetic, or motion, cues to depth much earlier in development. One-month-olds can detect spatial information using the "looming" cue that specifies impending collision (Yonas, 1981). Infants detect bidirectional motion by 6 weeks (Wattam-Bell, 1996a) and by 10 weeks show a preference for it, as compared with unidirectional motion (Bertenthal & Bradbury, 1992; Wattam-Bell, 1996b). Four-month-olds perceive 3-D shapes from kinetic displays (Kellman, 1984; Kellman & Short, 1987). Yonas and colleagues used a transfer-across-cues paradigm to demonstrate kinetic shape perception. Following habituation to a kinetically specified shape, infants preferred a novel static binocularly specified shape (Arterberry & Yonas, 1988; Yonas, Arterberry, & Granrud, 1987). Five- and 7-month-olds also reach preferentially for a closer object (Granrud, Yonas, & Pettersen, 1984). Craton and Yonas (1988) also found that, between two computer-generated surfaces, 5-month-olds reach more frequently for the surface that appears to be nearer.

However, over the years, researchers have given the most attention to the development of depth perception from bin-

ocular stereopsis. Early studies have generally supported the notion that stereopsis develops between 3 and 4 months of age when infants track binocularly specified objects (Birch, 1993; Fox, Aslin, Shea, & Dumais, 1980; Held, Gwiazda, Brill, Mohindra, & Wolfe, 1979). Some recent studies (e.g., Wattam-Bell, 2003) have reported the midpoint for the emergence of stereopsis at 13–14 weeks; however, Brown and Miracle (2003) reported possible evidence of stereopsis as early as 8.6 weeks and pointed out that this much earlier estimate is based on a particular definition of stereopsis (i.e., infants' sensitivity to binocular disparity) and may not reflect infants' perception of depth *per se*.

However, there is another potent, unambiguous depth cue that may develop at the same time as, and perhaps even earlier than, stereopsis, because it is based on motion cues that may be already available to the developing visual system (Kellman & von Hofsten, 1992). Motion parallax is a monocular depth cue that arises from the relative motion of objects at different distances and that is created when an observer translates laterally. As the observer translates, gaze is maintained on a particular object in the scene through the activity in a number of eye-movement systems (Miles, 1998). Objects located nearer than the observer's point of gaze have a relative movement in the direction opposite to that of the observer's movement, whereas objects located farther away have a relative movement in the same direction as the observer's movement. Furthermore, relative velocity is also a cue to relative depth in motion parallax. Objects nearer to the point

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of gaze move more slowly across the visual field than do objects more distant from the fixation point.

Motion parallax has been recognized as an important source of depth information for some time. Gibson (1950) originally called it "motion perspective," and Bower (1966) hailed it as the most effective depth cue in infancy, superior even to binocular disparity. Many noninfant studies of motion parallax have shown it to be a very powerful and unambiguous cue to depth. Recent work in human adults (Nawrot & Joyce, 2006) and monkeys (Nadler, Angelaki, & DeAngelis, 2006) has revealed that the visual system relies on an extraretinal pursuit eye movement signal for the recovery of unambiguous depth from motion parallax. Of particular relevance to the present study, von Hofsten (2004) has shown that pursuit eye movements mature early, approaching adult values (with individual variation) by 3 months of age.

Motion parallax has received very little attention from developmental researchers over the years, and it is generally misunderstood, even in textbook descriptions (Ono & Wade, 2006). There are a few studies of motion parallax and distance perception in children and teens (Carpenter, 1979; Degelman & Rosinski, 1979; Yonas & Hagen, 1973); however, regarding motion parallax in infancy, there are only two reports. Von Hofsten, Kellman, and Putaansuu (1992) used a real-object apparatus to test 3.5-month-olds: Infants were habituated to the movement of three rods aligned in the frontoparallel plane. The movements of the middle rod were contingent on those of the infant seat, creating motion parallax. Following habituation, infants looked longer on a test trial in which a static version of the display was depicted, in which the rods were aligned (a presumed novel configuration), as compared with a triangular test version of the display, where the middle rod was displaced by 15 cm relative to the side rods and therefore was presumed to be a familiar configuration because it was the actual distance of motion parallax simulated by the contingent movement of the infant/chair. This result disappeared in a second experiment when the motion of the infant chair was lowered from 0.32°/sec to 0.16°/sec. Von Hofsten et al. (1992) concluded that infants in their study were sensitive to the contingent motion, which is not depth from motion per se. They were therefore not able to make any firm conclusions about infants' sensitivity to depth from motion parallax.

The second study of motion parallax in infancy was by Yonas, Condry, and Botzet (1995), who used preferential reaching within a real-object apparatus. Similar to von Hofsten et al. (1992), the movement of a toy that the infant viewed was yoked to the movement of the infant seat. Unlike von Hofsten et al. (1992), Yonas et al. (1995) used a monocular viewing condition to control for possible binocular depth cues. They found that 6-month-olds, but not 5-month-olds, reached more often toward the apparently nearer toy, suggesting that they perceived the depth. Although the use of a meaningful, externally oriented measure, such as reaching, is clearly valuable in infant research, it may not be the optimal measure for motion parallax if we presume to find it in very young infants who have not developed an ability to reach with great reliability.

Because motion parallax relies on motion-carried information and because infants are sensitive to motion and depth-from-motion cues at an early age, we might expect to find evidence of sensitivity to motion parallax as early as the onset of sensitivity to binocular disparity. However, the two previous studies on motion parallax in infancy do not allow for strong conclusions. In their study, von Hofsten et al. (1992) could not rule out binocular cues because they did not have a monocular condition and because their conclusions are limited to the perception of contingent motion, not depth. Because infants in the Yonas et al. (1995) study were older than the median reported age for stereopsis, the results do not allow for conclusions about the age of onset of motion parallax.

The present experiment set out to address the questions of whether infants are sensitive to unambiguous depth specified from motion parallax and, if so, when this sensitivity begins to develop. In contrast to some previous research on depth from both motion parallax and stereopsis, we used a stimulus designed to measure unambiguous depth perception, not shape perception, motion direction, or object recognition. Because there were so few studies to guide our hypothesis concerning the age of onset of motion parallax, we used a longitudinal design to investigate this more closely.

METHOD

Participants

Participants included 11 infants (6 boys, 5 girls) with no reported birth complications. Infants were tested longitudinally, beginning at ages between 8 and 12 weeks and continuing at 2- to 4-week intervals when possible.

Stimulus

We used a random-dot stimulus (Rogers & Graham, 1979) that appears (to adult observers) as a 3-D corrugated surface undulating in depth along the vertical axis. The stimulus comprised three thousand 6.5×6.5 min white dots on a black background. The stimulus window subtended $20.5^\circ \times 20.5^\circ$ at a viewing distance of 45 cm. Within this stimulus window, the motion parallax stimulus depicted 1.5 cycles of sinusoidal depth corrugation over the 20.5° stimulus height, giving a stimulus spatial depth frequency of 0.07 cycles/degree. The additional 0.25 cycles of corrugation at the top and bottom of the stimulus helped emphasize the depth curvature of the stimulus, as compared with a stimulus that subtended only a single cycle of depth corrugation.

The depth corrugation was created by translating dots within the stimulus window with horizontal velocities that varied vertically across the stimulus according to a sinusoidal function. Dots that translate in opposite directions appear at opposite depth relative to the fixation point. Dots with higher velocities appear to be deeper than the zero depth found at the vertical midline of the stimulus.

For adult observers (and presumably for infants), the unambiguous perception of near/far depth phase of the motion parallax stimulus depends on the relationship between dot movement and stimulus window movement (Nawrot & Joyce, 2006). For example, rightward translation of the stimulus window elicits a rightward pursuit eye movement. In such a case, dots moving rightward within the stimulus are perceived as near in depth, and leftward moving dots are perceived as far. In the absence of the pursuit eye movement, the stimulus is perceptually depth-sign ambiguous (Nawrot & Joyce, 2006). Lateral head movements are not a requirement for the unambiguous perception of depth from motion parallax with these displays and are involved only insofar as they help elicit a pursuit eye movement (Nawrot & Joyce, 2006).

In each trial, the stimulus window started at the center of the screen and translated 10° side to side (1.5 cycles, 30° total stimulus extent) across the black flat-screen monitor at rate of approximately 0.15 Hz, or 3.3°/sec. This range of motion velocity is well within the parameters used by von Hofsten (2004) to measure smooth pursuit at this age. The initial direction (left or right) of stimulus window translation in each trial was determined randomly. For each trial, the stimulus was presented for a total of 10 sec.

During habituation trials, the stimulus depth phase was presented such that the upper half of the stimulus appeared (to adult observers) to be near in depth, whereas the lower half appeared to be far. This depth phase was reversed in the first test trial after habituation. Depth was removed from the stimulus in the last test trial by presenting a single frame of the stimulus within the stimulus window as it moved from side to side. Different stimulus exemplars were generated prior to each experiment, and the particular exemplar was chosen at random for presentation at each trial.

Procedure

Infants were tested individually on an average of four occasions, each separated by an interval of not less than 2 weeks. After informed consent was obtained, the infant's left eye was patched with a sterile, disposable adhesive bandage. The infant was seated on his/her parent's lap and faced the monitor in a three-sided enclosure to minimize distraction. Looking time was video recorded using an out-of-sight camera. In a separate control room, an observer viewed the infant on a monitor and recorded looking time on each trial by depressing a key when the infant was judged to be looking at the stimulus.

Each trial began by using sound and flashing, colored LEDs to bring the infant's attention toward the monitor. Following the infant-control habituation paradigm (see Horowitz, Paden, Bhana, & Self, 1972), we presented infants with the Rogers and Graham (1979) motion parallax stimulus. The *online* habituation criterion was defined as a 50% decline in proportion of looking from the average of the first two trials. When the infant reached that criterion, the two test trials were presented.

The first test trial presented the identical motion parallax stimulus with only the opposite depth corrugation: The top section appeared in far depth, and the bottom appeared in near depth. In pre-pilot testing, adult observers who were uninformed of the procedure showed marked dishabituation to this depth change of the stimulus. The second test stimulus depicted a flat version of the stimulus—essentially, a single frame of the motion-parallax stimulus—which translated across the monitor face at the same frequency as the habituation stimuli. We expected that this flat version of the stimulus would serve as a greater depth change, as compared with the more subtle depth-sign change from the previous trial, therefore giving us another opportunity to observe any possible dishabituation in our infant observers. Moreover, dishabituation to the flat stimulus would allow us to judge whether infants were sensitive to depth from motion in general, similar to previous research using depth-sign ambiguous figures (e.g., rotating spheres or cubes).

RESULTS

Figures 1A and 1B show single testing sessions for 1 infant (D.M.) at 15–22 weeks. At 15 weeks, D.M.'s looking time declined steadily across trials, including the 2 test trials. By 22 weeks, this pattern changed to one of recovery of looking to the 2 test trials, an indication that D.M. perceived a change in the stimulus. It took an average of 8 trials for infants to reach habituation criteria. One infant was dropped from further analyses for slow habituation (more than 12 trials), similar to von Hofsten et al.'s (1992) attrition rate for this same problem. All 10 remaining infants dishabituated to the flat stimulus by their final testing session; 1 infant failed to dishabituate to the depth-reversed

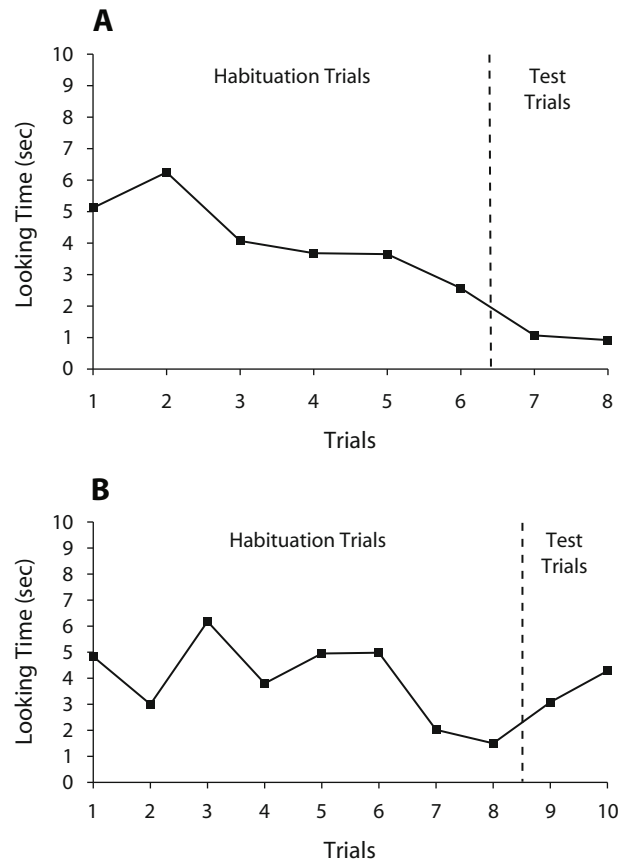


Figure 1. Single-test sessions for infant D.M. at 15 weeks (A) and 22 weeks (B). Both sessions began with similar initial looking times but led to different outcomes. After the infant met the habituation criteria, the two test trials were presented: the depth-reversed stimulus, followed by the flat stimulus. Panel A illustrates that, at 15 weeks, D.M.'s looking time continued to decline across Test Trials 7 (depth-reversed) and 8 (flat). Panel B illustrates how, by 22 weeks, D.M.'s looking time increased on both Test Trials 9 (depth-reversed) and 10 (flat), even recovering to the level of the initial trial.

stimulus on his last test session at 19 weeks and was not able to return for further testing.

Figure 2 illustrates an entire longitudinal data set from 1 infant, from 15 to 25 weeks, and includes five individual testing sessions. The *y*-axis is coded as *difference in looking time* from the last habituation trial to the test trial and illustrates how the infant's pattern of looking changed from habituation (points below the zero horizontal line) to dishabituation (points above the line) with age. These data are from the depth-reversed version of the stimulus.

On average, the infants dishabituated to the flat stimulus by 16.9 weeks, which is an average of the ages for which infants in this study first showed recovery of looking time to the test stimulus. However, this most likely overestimates the age of onset of sensitivity to motion parallax, because 6 of the 10 infants were dishabituating to this stimulus at their earliest testing session. Individual infants dishabituated to the flat stimulus as early as 11 and 14 weeks. Data from the flat stimulus are displayed in Figure 3. The *y*-axis is coded as proportion of looking time on the last test trial divided by

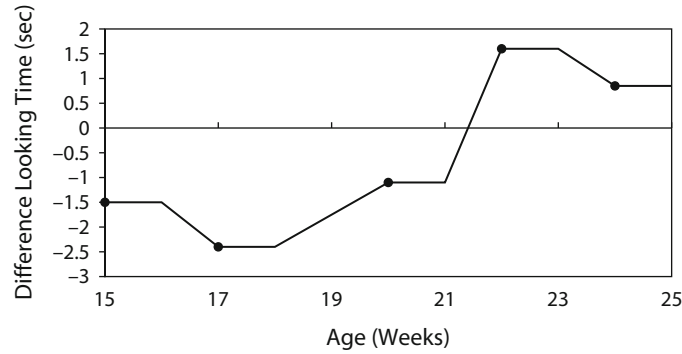


Figure 2. Five test sessions for infant D.M. illustrate how the pattern of looking time changes from continued habituation (data below the horizontal zero line) to dishabituation (data above the line) to the test stimulus.

the infant’s looking time on the previous trial. Therefore, a value below the $y = 1$ horizontal line indicates habituation, whereas values above the line indicate dishabituation. As can be seen in Figure 3, many of the individual infant data fall above this dotted line, even at the earliest ages.

For the depth-reversed stimulus, individual infants showed dishabituation as early as 10 and 12 weeks, with the group dishabituating on average at 16.7 weeks. Figure 4 displays the results from the depth-reversed stimulus for all 10 infants. The y -axis represents proportion of looking time on the last test trial divided by that on the last habituation trial. A value below the $y = 1$ horizontal line indicates habituation; values above the line indicate dishabituation.

To more closely examine a possible developmental timeline for change, Figure 5 illustrates the same data as those in Figure 4, but with the addition of a least-squares trend line. A regression equation fit to the data produces

an R^2 value of .26 [$F(1,37) = 12.5, p = .001$], and the $y = 1$ intercept is estimated at 14 weeks.

These data represent the first evidence that very young infants are sensitive to the unambiguous depth signal that is provided by motion parallax. Our estimates place the development of sensitivity to motion parallax at 14–16 weeks on average, with individual variability that demonstrates that performance is possible as early as 10–12 weeks. This places the development of motion parallax within an age range similar to that for the development of sensitivity to depth from stereopsis. Because all three versions of the stimulus were in motion (habituation, depth-reversed, and flat), the infants did not respond on the basis of kinetic depth cues alone, a criticism levied on previous research (i.e., Arterberry & Yonas, 1988). And although at the older ages these infants might have developed binocular stereopsis, these data were collected monocularly.

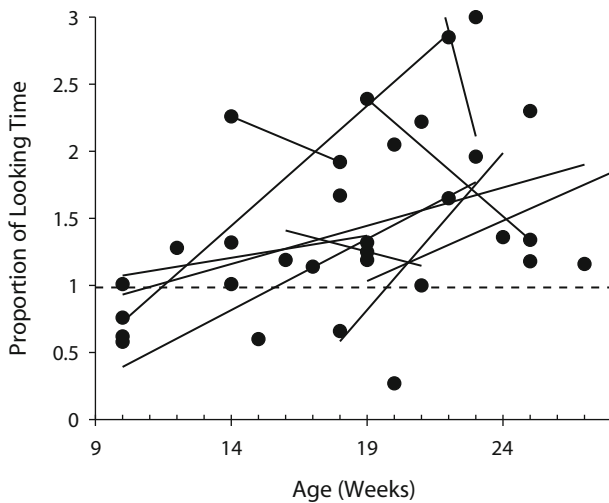


Figure 3. Proportion of change in looking time from the infant’s last looking trial to the test trial against age for the flat stimulus plotted for all 10 infants. For each infant, a least-squares trend line is fit to their data to illustrate the slope relative to the $y = 1$ dotted line. Data points falling below this line indicate continued habituation to the test stimulus; points above the line indicate dishabituation.

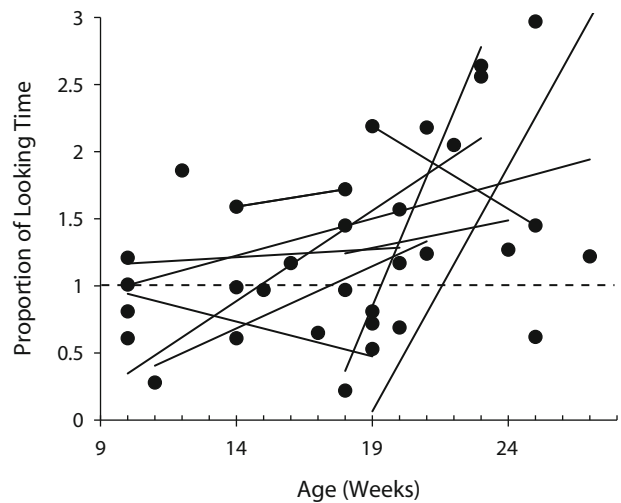


Figure 4. Proportion of change in looking time from the last habituation trial to the test trial against age for the depth-reversed stimulus plotted for all 10 infants. For each infant, a least-squares trend line is fit to their data to illustrate the slope relative to the $y = 1$ dotted line. Data points falling below this line indicate habituation to the test stimulus; points above the line indicate dishabituation.

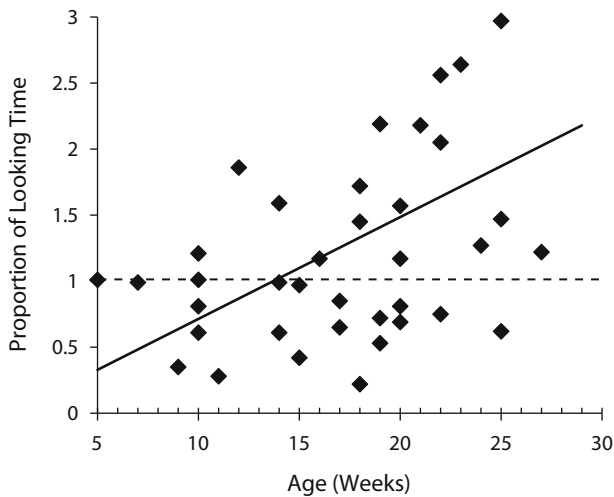


Figure 5. Scatterplot data from all 10 infants are plotted as proportion of change in looking time from the last habituation trial to the test trial against age for the depth-reversed stimulus. A least-squares trend line is fit to the data to illustrate the slope relative to the $y = 1$ dotted line.

DISCUSSION

The present study provides the first strong evidence that infants are sensitive to the cue of motion parallax for the unambiguous perception of depth. Furthermore, we estimate that infants become sensitive to depth from motion parallax between 14 and 16 weeks on average, within the same age range during which they are developing sensitivity to depth from binocular stereopsis.

Results from the present study are in keeping with previous literature on depth from motion studies in 4-month-olds. In their study of depth from motion, Arterberry and Yonas (1988) used rotating kinetic depth effect (KDE) cubes. Interestingly, rotating KDE figures spontaneously reverse in depth, according to adult observers, suddenly switching from rotating leftward to rightward, and vice versa. Failure to habituate to a perceptually reversing figure may be the reason for the high attrition rate reported by Arterberry and Yonas. Perhaps infants in their study became fussy during habituation trials because they perceived spontaneously alternating figures, not presumably familiar figures, as is the intention in a habituation/dishabituation experiment.

Because infants in the present study showed a pattern of dishabituation, we infer that they used pursuit to disambiguate the stimulus, much like adult observers (Nawrot & Joyce, 2006). In the absence of pursuit, the motion parallax stimulus is depth-sign ambiguous. This means that either depth phase of the corrugation may be perceived and that the perceived phase often reverses as the observer views the stimulus. If the infant's perception was ambiguous and reversing, it is unlikely that the infant would find it novel when the stimulus was changed. If this were the case, even this new stimulus could be perceived in both depth phases.

It also remains possible, but unlikely, that infants did not dishabituate to a change in the perception of depth

portrayed in the stimulus, but dishabituated to a stimulus change. In this low-level alternative explanation, the infants responded to a local stimulus change in the relationship between stimulus window movement and dot movement. First, consider that, at all times, roughly equal numbers of dots were moving leftward and rightward within the stimulus window. Also consider that every moving dot translated both leftward and rightward equally within the stimulus window. To dishabituate to this low-level stimulus change, the infant would have needed to detect that a particular region of dots that moved leftward during leftward stimulus window translation was now moving rightward during leftward stimulus window translation.

We find this alternative explanation very unlikely because naive adult observers, who very quickly and easily detect the perceptual depth change, usually are unable to describe the stimulus changes that produced their perceptual change. Indeed, it is quite complicated for an observer to keep track of, and then to detect a change in, the low-level stimulus variables. Moreover, an identical argument could be made in the case of binocular stereopsis. That is, we really do not know whether infants perceive depth from stereopsis or whether they respond to retinal changes, such as the monocular positions of stimuli that create retinal disparity when compared between the two eyes. Although the criticism is identical, few would offer such an alternative explanation for the case of binocular stereopsis.

The habituation paradigm has also suffered criticism. There are many issues here, including how and where to set the habituation criteria and whether to use control groups or conditions. In the present study, we used infant-controlled habituation and the standard 50% decline in the average of the first two trials to set our criterion. Because this was a longitudinal study designed for exploratory purposes, we did not include a control group. However, these choices limited the generalizability of our findings. In future research, we plan to implement a cross-sectional age design and to include multiple posthabituation conditions. The use of multiple posthabituation test conditions (or control conditions) will allow us to examine any possible regression to the mean effects. That is, we can compare results from continuing habituation trials with test trials for possible looking-time artifacts. The cross-sectional design with more participants at more ages will allow for direct statistical analysis of developmental trends.

If smooth pursuit eye movements disambiguate depth signs for infants in the same way as for adults, the next step in our research is to collect eye-movement recordings while infants engage in a motion parallax task. Smooth pursuit is quite mature at 3 months of age (the lower age limit on most depth-from-motion studies) and improves significantly between 2 and 5 months (Rosander & von Hofsten, 2002; von Hofsten & Rosander, 1997).

Considering the role of pursuit eye movements in motion parallax (Nawrot & Joyce, 2006), the perception of unambiguous depth from motion parallax might emerge only when pursuit gain approaches mature values. If so, motion parallax might develop before binocular stereopsis and perhaps even serve as the foundation of the depth

processing networks in cortical area MT. The demonstration of a role for pursuit in the depth/motion selectivity in MT cells (Nadler et al., 2006) certainly suggests that this is a possibility. Therefore, it is crucial that future research also directly compares a motion parallax and stereopsis version of the same stimulus to be tested under identical conditions when the smooth-pursuit eye movement system has matured appropriately.

There are many studies showing low-level interactions between binocular stereopsis and motion parallax (e.g., Nawrot & Blake, 1989), but it is still unclear how these interactions, and their underlying neurophysiological processes, develop. Infant studies may reveal whether motion perception, pursuit eye movement gain, depth from motion parallax, and binocular stereopsis develop sequentially, one aiding in the development of the next. In this hypothesis, the development of motion parallax serves as a developmental foundation for stereopsis in higher cortical areas, proving functional links among the correlated eye movement, motion parallax, and stereopsis dysfunction seen in esotropia (Nawrot, Frankl, & Stockert, 2004).

AUTHOR NOTE

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