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Four-Month-Olds' Discrimination of Optic Flow Patterns Depicting Different Directions of Observer Motion

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One of the most powerful sources of information about spatial relationships available to mobile organisms is the pattern of visual motion called optic flow. Despite its importance for spatial perception and for guiding locomotion, very little is known about how the ability to perceive one's direction of motion, or heading, from optic flow develops early in life. In this article, we report the results of 3 experiments that tested the abilities of 4-month-old infants to discriminate optic flow patterns simulating different directions of self-motion. The combined results from 2 different experimental paradigms suggest that 4-month-olds discriminate optic flow patterns that simulate only large (> 32°) changes in the direction of the observer's motion through space. This suggests that prior to the onset of locomotion, there are limitations on infants' abilities to process patterns of optic flow related to self-motion.

A central goal of spatial perception is to determine the direction and distance of objects or surfaces in the environment relative to the observer. Under normal circumstances, both direction and distance perception depend on multiple sources of information within a single sensory modality and involve the integration of information across modalities. Although the nature of this process of multisensory integration is not well understood in adults, it poses a considerable challenge for the mature nervous system and, presumably, an even greater challenge for a rapidly developing nervous system like that found the human infant. For this reason and

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Supplementary materials to this article are available on the World Wide Web at http:// www.infancyarchives.com.

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others many investigators concerned with perceptual development believe that spatial processing may function quite differently in very young infants compared with older children or adults (Newcombe & Huttenlocher, 2000; Yonas & Granrud, 1985). This article focuses on a form of spatial perception that has received considerable recent attention in the adult literature—the perception of an observer's direction of self-motion or heading—but has been studied relatively little in young infants.

Determining an observer's direction of heading is vital for controlling posture, locomotion, and avoiding collisions. Perhaps the most important source of information about heading is optic flow, the pattern of visual motion generated by an observer moving through a rigid environment (Gibson, 1966). Extensive empirical investigations with adults have shown that from optic flow patterns alone an adult observer can determine heading and the direction, distance, and orientation of objects and surfaces in the environment (reviewed in Warren, 1998). Under a variety of conditions, adult observers determine their direction of heading from optic flow to within 1° of visual angle (Royden, Crowell, & Banks, 1994; Warren, Morris, & Kalish, 1988), an accuracy that is more than sufficient for steering across a wide range of speeds (Cutting, Springer, Braren, & Johnson, 1992). Adults' heading perception is based on a number of cues including the perception of where in the visual field the focus of expansion (FOE; Gibson, 1966), the central point from which all moving elements appear to emanate, is located. Furthermore, neurophysiological studies have shown that optic flow selectively activates specific regions of the visual association cortex in nonhuman primates (Duffy & Wurtz, 1991, 1997) and homologous areas in human adults (de Jong, Shipp, Skidmore, Frackowiak, & Zeki, 1994; Morrone et al., 2000). Consequently, studying how human infants discriminate between optic flow patterns that specify different directions of heading may help to answer more general questions about spatial perception and action planning early in life and what factors shape development in this domain. Indeed, the focus of the studies reported in this article is to determine the extent to which young infants who are not yet able to sit erect or crawl can discriminate between patterns of optic flow that simulate different directions of heading.

Rudimentary sensitivity to some patterns of optic flow emerges early. For example, in the first weeks of life infants begin to respond with eye blinks and backward head movements to patterns of optic flow which specify an impending collision with an object approaching the face (e.g., Yonas, Pettersen, & Lockman, 1979). However, the behavior develops rather slowly. Not until approximately 3 months of age do infants blink 60% to 75% of the time (Nañez, 1987; Yonas et al., 1979). Further, Nañez and Yonas (1994) observed that both 4- and 8-month-old infants showed greater blinking and backward head movements to optically expanding textures when the elements' motions were on a single depth plane rather than on multiple depth planes. Thus, in addition to discriminating information about an object's extent in depth, 4-month-olds also appear to discriminate some information about the form of the approaching surface (Nañez & Yonas, 1994). Other aspects of perception from motion also appear to develop early. Two-month-olds appear to be able to distinguish some differences in shape from motion information alone (Arterberry & Yonas, 1988, 2000). Four-month-old infants discriminate changes in object form from kinetic information (reviewed in Kellman, 1993) and discriminate biologically plausible motion in point-light displays from implausible patterns of motion (e.g., Bertenthal, Proffitt, Kramer, & Spetner, 1987). In short, sensitivity to some patterns of optic flow, especially those associated with detecting collisions and perceiving aspects of object form, develop relatively early.

A second domain in which sensitivity to visual motion and optic flow has been examined focuses on movements of the head, hips, and torso that are associated with the stabilization and control of posture. Lee and Aronson (1974) demonstrated that oscillating patterns of optic flow presented in a moving room apparatus could induce 13- to 16-month-old children to sway or even fall down. Subsequent research has focused on even younger infants who are not yet able to walk or who are just beginning to walk. There are reports that newborn infants make directionally appropriate lateral head movements in response to moving stripe patterns (Jouen & Lepecq, 1989), and that within the first 1 to 2 months of age infants move their heads in response to oscillating patterns of visual motion (Pope, 1984). Although these studies with young infants are provocative, Bertenthal and colleagues (1989, 1997) have carried out the most extensive studies of infants' postural responses in relation to visual motion. These studies have indicated that visual motion produced by a moving room can induce directionally appropriate compensatory shifts of the body's center of pressure in 5-month-olds (Bertenthal & Bai, 1989; Bertenthal, Rose, & Bai, 1997). The magnitude and consistency of response is considerably lower than that observed in 7-, 9-, and 11-month-old infants. However, in the second half of the first year of life, the regularity and strength with which oscillating optic flow patterns evoke compensatory postural responses increases (Ashmead & McCarty, 1991; Bertenthal & Bai, 1989; Bertenthal et al., 1997) and becomes functionally specific to the direction of imposed visual motion (Ashmead & McCarty, 1991).

The fact that very young infants can respond to forward or backward patterns of visual motion with forward and backward movement of the head and body tells us that young children are sensitive to some aspects of the direction of visual motion, that this sensitivity can influence movement in different action systems, and that there are developmental changes that occur in the coupling between perceptual information and motor responses. However, these data by themselves do not allow us to quantify infants' abilities or answer specific questions about what actually is developing. The relationship between heading perception from optic flow and postural control is not well understood in adults, but effective balance control and steering presumably require both precision in motion perception and the capacity to produce directionally appropriate actions. Unfortunately, there is scant evidence about infants' abilities to discriminate between optic flow patterns that specify different directions of motion other than distinguishing between forward and backward movement. We do not yet know at what age infants' accuracy is sufficient for locomotion or steering, nor do we know how that accuracy changes over time. These are questions that the moving room studies provoke but do not fully answer. Moreover, most previous studies on infants' perception of self-motion, including those that used the moving room paradigm, did not effectively isolate optic flow from other visual cues, specifically optic expansion. Accordingly, we cannot make meaningful comparisons between infants' abilities and the rich literature that exists on related questions in adults. As such, more precise estimates of the extent to which infants are sensitive to relatively small changes in the direction of self-motion specified by optic flow would seem to fill an important gap in the literature.

At the outset, there are several factors that may constrain young infants' abilities to discriminate between optic flow patterns that simulate different directions of heading. One is the precision and sensitivity of low-level motion processing systems. Sensitivity to the speed and direction of visual motion is quite poor in young infants relative to adults. This observation is important to the current argument because sensitivity to the distribution of the speed of moving elements in optic flow is crucial for extracting meaningful information about self-motion and environmental layout. It appears that the minimum (~ 5°/sec) and maximum (~ 12°/sec) speeds detectable by 8- to 10-week-olds in random dot patterns are an order of magnitude worse than adults (see review by Wattam-Bell, 1996). By 15 to 20 weeks, infants are sensitive to uniform motion at up to 30º/sec, but sensitivity remains substantially below adult levels. Unfortunately, there is minimal evidence about the development of velocity sensitivity in infants older than 15 to 20 weeks.

On the other hand, determining the direction of individual moving elements and the pattern of their distribution may be even more important for detecting changes in heading (Banton & Bertenthal, 1995, 1997). Indeed, quantitative analyses by Crowell and Banks (1996) suggest that precision in discriminating differences in direction is the most important variable in accounting for adults' abilities to discriminate heading direction from optic flow. In general, adults detect direction differences of less than 1° (de Bruyn & Orban, 1988). Unfortunately, surprisingly little is known about direction discrimination early in life. Manny and Fern (1990) found that when using an optokinetic nystagmus procedure, 1- to 3-month-old infants could discriminate 45º changes in the direction of a uniformly moving grating. A more recent study (Banton, Bertenthal, & Dobkins, 2001) showed large improvements in the ability to discriminate direction of motion between 6 and 18 weeks of age. Direction thresholds could not be obtained at 6 weeks, but reached 17° by 18 weeks. This particular paradigm involved the presentation of a region of uniformly moving dots against a background moving in a uniform, but different direction. Moreover, to elicit sufficient interest in the display, Banton and colleagues (2001) fashioned their display so that the target region itself changed position relative to the background. The results of this clever study illustrate that sensitivity to changes in the direction of uniformly moving patterns is poor early in life, and although it improves markedly, remains well below adult levels at the oldest age tested of about 4 months. How sensitivity to change in the direction of uniformly moving fields occurs over the remainder of the first year of life and how improvements in low-level motion sensitivity contribute to accurate optic flow perception are important, but as yet unanswered questions.

Nevertheless, sensitivity to uniform motion may not provide the best comparison if our goal is to understand how the discrimination of optic flow patterns experienced by mobile observers develops. Optic flow derived from movement of an observer through even the simplest of visual environments results in patterns of motion that are usually nonuniform both in speed and in direction. Virtually the only natural circumstance in which optic flow that is roughly uniform in speed and direction will be generated is when the observer moves laterally parallel to a vertically oriented surface. Even in this situation, the speed of the moving elements will vary as a function of vertical displacement from the line of sight. Indeed, as Gibson (1966) observed, it is the pattern of nonuniformity—the gradients in the direction and speed of the moving elements in the optic array—that provide the most useful information to moving organisms about their own motion and the layout of the environment. Consequently, to understand the development of sensitivity to optic flow, it may be most informative to examine infants' abilities to discriminate optic flow patterns that simulate different directions of observer motion, which maintain the more ecologically valid pattern of speed and direction gradients.

In the studies described here, the goal was to quantify how accurately young infants who are not yet able to crawl or walk could discriminate between optic flow patterns that simulated different directions of heading. Unlike the previous moving room studies, but consonant with a large amount of literature in infant visual psychophysics, visual discrimination was the critical variable of interest. In Experiments 1 and 2, a looking time habituation and recovery method was used to examine whether infants who habituated to an optic flow display would show looking time increases to displays when the direction of heading changed. In Experiment 3, we used a more sensitive psychophysical measure of sensitivity to changes in heading direction based on the classic forced-choice preferential looking (FPL) method (Teller, 1979). The results from all three experiments provide converging evidence that the visual discrimination of optic flow patterns specifying different directions of observer motion undergoes considerable postnatal development.

EXPERIMENT 1

Methods

Participants. Thirty-one 4-month-old (117–129 days; 16 female) healthy infants participated. All were born between 38 and 42 weeks gestational age as determined from due dates estimated by the mothers' physicians. The infants were recruited by telephone from information contained in birth announcements published in the newspaper. Appropriate informed consent procedures were followed.

Apparatus. The stimulus display was generated on a 32-in. Sony video monitor controlled by a Macintosh G3 microcomputer running Matlab 5.2 and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) routines. The sides of the monitor were masked with dark cloth, and the entire testing apparatus was located in a quiet testing room in which the ambient lighting was dimmed. Participants sat in a padded infant seat positioned 90 cm from the center of the screen. The observer viewed the infant's face and eyes by means of a low-light-sensitive video camera mounted above and behind the display.

Display. The display consisted of a series of computer-generated movies that simulated linear translation parallel to a ground plane at a speed of 30 m/sec. Each movie consisted of 50 individual frames presented at 30 frames per second, which looped continuously until the experimenter ended the trial with a computer key press. Each frame of the display consisted of 67 white dots (72 cd/m^2) presented on a black background (0.1 cd/m^2). At the specified viewing distance, each dot was 0.4° square, the viewing region was 40° (H) by 30° (V), and the dot density was .11 dots per degree squared. The mean and median optical speeds of the dots were 21.3°/sec and 12.1°/sec, respectively. The locations of the dots were chosen at random for each trial, subject to the constraint that dot positions were uniformly distributed along the region of the simulated ground plane, which was visible at the start of a trial. A simulated eye height of 87.5 cm and a horizon truncated at 5,000 cm were used to compute dot positions. Dots that disappeared from view during a frame reappeared on the next frame at the simulated horizon to create the illusion of continuous motion in depth. Figure 1 shows a schematic of the display. QuickTime movies of the displays are available on the *Infancy* Web site at www.infancyarchives.com.

Procedure. An infant-controlled habituation technique was used to determine whether babies discriminated between displays that depicted different directions of heading. During the habituation phase, all participants viewed repeated presentations of a display that simulated translational motion in the forward (0°) or backward (180°) direction. Infants were randomly assigned to either the forward group, which viewed 0° movement during habituation, or the backward group, which viewed 180° motion. During the test phase, all infants viewed two trials of

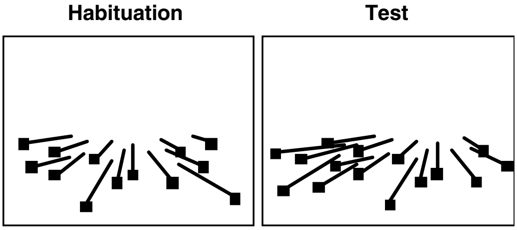

FIGURE 1 Schematic of optic flow display used in Experiments 1 and 2. The dots are depicted in black and the paths of the dots are indicated to improve the readability of the figure. In the actual display, the dots were white presented against a black background.

the familiar direction presented during habituation and two trials of the novel direction presented in alternating order. An observer, who did not know the experimental condition to which an infant was assigned or the heading direction of the current trial, monitored the infant's direction of gaze and pressed keys on the computer when the infant fixated the display or looked away. The computer recorded accumulated look time to the display in a given trial until the baby looked away for 1.5 sec or a total of 60 sec of look time had elapsed. The habituation display was presented on subsequent trials until the look time within a trial dropped below the habituation threshold or a maximum of 15 trials had been presented. The habituation threshold was computed following the procedure outlined by Ashmead and Davis (1996). Specifically, following the fifth habituation trial, the computer fit a second-order polynomial to the look time data. When the fitted look time following a given trial dropped below 50% of the value of the fitted look time for the first habituation trial, the habituation phase ended and test trial presentation began.

The test trials consisted of optic flow movies depicting movement of the observer in both the familiar and novel heading directions. The test trials were displayed in alternating orders of presentation that were counterbalanced across infants. The computer stored heading values and accumulated look times in a data file for subsequent analyses.

Analysis. Reliability was assessed by having a second observer code 20% of the trials from videotape. The correlation between look times determined online and those assessed offline was .98. A 2 (familiar vs. novel) × 2 (direction observed during habituation) repeated measures analysis of variance (ANOVA) was used to analyze the look time data, which were collapsed across the two orders of presentation. Raw look times were subjected to a square root transformation prior to analysis to adjust for the nonnormality of the distribution. Data were transformed back into their original units for plotting and data summaries.

Results

There were no differences in mean look times to the two different displays during the habituation phase. However, the mean look time to the test displays depicting a novel direction of heading (*M* = 13.3 sec, *SD* = 11.9) was larger than the look time to the test displays depicting the familiar direction of heading (*M* = 8.0 sec, *SD* = 8.4), as indicated by a significant main effect for novelty, *F*(1, 48) = 10.07, *p* = .0048. There were no other effects or interactions that reached statistical significance. Figure 2 shows the results collapsed across order of presentation.

Discussion

Following a period of familiarization with an optic flow display simulating one direction of motion, infants' mean look times were larger to a novel display that differed by 180° in heading. This suggests that 4-month-old infants could discriminate between the displays in which the direction of heading depicted by optic flow differed by 180°. The result is broadly consistent with other research where infants at this age have been shown to discriminate objects moving forward from those moving backward (Schmuckler & Li, 1998; Yonas et al., 1979) by

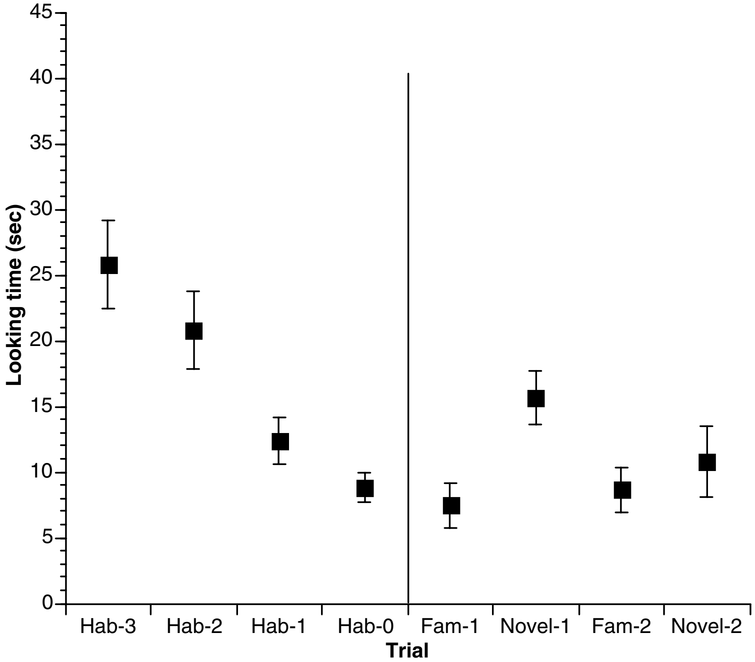

FIGURE 2 Summary of data from Experiment 1 depicting the mean (± 1 *SE*) look times by trial. During the habituation phase (Hab-3 to Hab-0), infants viewed either a forward (0°) or backward (180°) moving ground plane pattern. During the test phase, infants viewed both the familiar (Fam) and novel (Novel) directions presented in alternating order twice. These data for the test trials are collapsed across the two orders of presentation.

making differential head movements and eye blinks with data showing that young infants make small, but measurable changes in posture in response to forward–backward motion in a moving room (Bertenthal et al., 1997). However, these data are the first to demonstrate that 4-month-old infants can discriminate between displays depicting different directions of self-motion from optic flow information alone. Moreover, the results build on previous findings by demonstrating that 4-month-olds are sensitive to direction of motion information contained in displays depicting only a ground surface. In particular, these results demonstrate that 4-month-olds' abilities to discriminate between optic flow patterns depicting different directions of motion are not confined to circumstances in which the visual information specifies a potential impending collision with the face.

Having demonstrated that infants do make discriminations between displays depicting large differences in the direction of motion, our next question was whether young infants could discriminate smaller changes in direction. As mentioned previously, adults tested under similar display conditions can detect changes in heading of less than 1° (Crowell & Banks, 1993; Warren et al., 1988). Based on the existing evidence about infants' sensitivity to visual motion, we predicted that 4-month-olds would be less sensitive than adults to displays in which direction of heading information changes. In pilot testing, we determined that 4-month-olds were insensitive to displays that differed in heading direction by 4° and 8°. We therefore elected to test discrimination between displays that differed by 16° in heading direction. We chose this angle for two reasons. We wanted to ensure that the focus of expansion would remain visible on the screen in all of our display conditions. We also wanted to ensure that the average change in direction of the moving dots was large. It turns out that due to the distortion induced by the projection of points on the ground plane onto the display surface, the mean direction of moving elements in our displays is 0° (downward) in the forward motion condition, but 63° when the direction of heading is 16°. As mentioned previously, the best available estimates suggest that 4-month-old infants can discriminate, on average, 17° changes in the direction of uniformly moving dots (Banton, Bertenthal, & Dobkins, 2000). Consequently, if the discrimination of these optic flow displays is based largely on detecting differences in the mean direction or orientation of the moving elements, then 4-month-olds should be able to discriminate displays that differ in simulated heading by 16°.

EXPERIMENT 2

Methods

Twenty 4-month-old (121–135 days; 11 female) infants recruited as previously described participated. The apparatus, display, and procedures were as previously described, with the following exceptions. Infants were familiarized with a display depicting motion along 0° or 16° headings and were tested with displays depicting both the familiar and novel direction of heading. Mean (21.3°/sec) and median (12.1°/sec) optical speeds for the 0° condition were identical to the values reported for the previous experiments. For the 16° heading condition the values were 34.6°/sec and 21.2°/sec, respectively. QuickTime movies of the displays are archived on the *Infancy* Web site at www.infancyarchives.com. Reliability was assessed as previously described. The correlation between online and offline judgments of look time duration was .91.

Results

There were no differences in mean look times between 0° and 16° during the habituation phase. Further, during the test phase the mean look time to the familiar direction (M = 10.3 sec, SD = 8.5) did not differ from the mean look time to the novel direction (M = 10.7 sec, SD = 9.9), $F(1, 40) = .79$, *ns*. No other main effects or interactions reached statistical significance. Figure 3 summarizes the results.

Discussion

These results indicate that 4-month-olds did not reliably distinguish between displays that simulated a 16° change in the direction of heading. Look time did not increase following a change from either the 0° or 16° display to the test display that depicted a different direction of self-motion. The results suggest that 4-month-old infants discriminate between optic flow displays only when larger changes in heading direction are simulated.

On the other hand, it is possible that factors specific to these testing conditions led to particularly poor performance. One factor specific to the habituation paradigm is memory demand. This habituation paradigm may place demands on infants' memory because responses during the test phase presumably tap into stored representations about the familiar optic flow pattern. It is possible that these memory demands made it less likely that infants would discriminate displays depicting small changes in heading when the displays were separated in time by several seconds. These habituation data themselves argue against this notion, in part, because there was no statistically significant effect of test trial order—presenting the novel pattern before the familiar pattern. Furthermore, Wattam-Bell (1996) successfully used habituation to examine motion sensitivity thresholds with 8- to 10-week-old infants. As a result, it is possible, but unlikely that memory demands of the habituation paradigm led to substantially lower estimates of infants' sensitivity than would be possible using another technique.

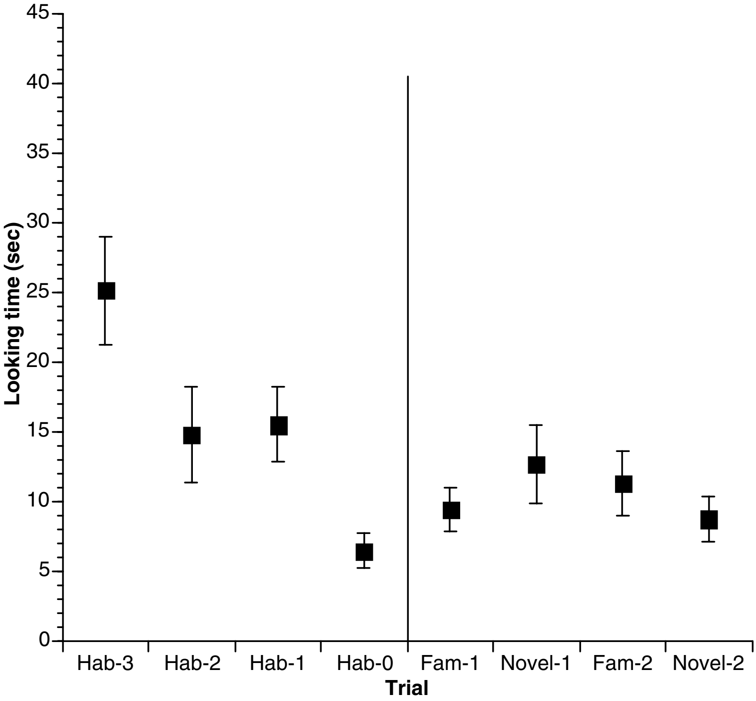

FIGURE 3 Summary of data from Experiment 2. During the habituation phase (Hab-3 to Hab-0), infants viewed either a left- or rightward pattern of motion deviated at 16° from the center of the display. During the test phase, infants viewed both the familiar (Fam) and novel (Novel) 0° direction of heading in alternating order.

Display-related factors may also have contributed to the lack of discrimination. For example, the restriction of optic flow information to a ground plane covering only the lower part of the visual field might also have diminished infants' performance. This sort of differential sensitivity is not shown in adults who show comparable heading detection thresholds whether viewing simulated translation along a ground plane, through a cloud of dots, or relative to a frontoparallel plane (reviewed in Warren, 1998). Nevertheless, infants may require larger areas of the visual field to be in motion to discriminate between displays that differ in simulated heading direction.

Similarly, it is possible that the rapid speed of observer motion (30 m/sec) simulated in the displays underestimated infants' actual abilities by depicting moving elements where optical speeds were outside of the infants' abilities to detect reliably. Mean and median speeds were 21.3°/sec and 12.1°/sec, for the 0° condition, and 34.6°/sec and 21.2 °/sec for the 16° condition. The mean optical speeds are high relative to published maximum sensitivities for 4-month-olds, but the median values are within these norms (Wattam-Bell, 1996). In any case, the speed distribution is highly skewed, so the median speed is probably a more appropriate measure of central tendency. Moreover, the optical speeds in Experiment 2 are comparable to the displays in Experiment 1 in which infants did discriminate. Adults' heading discrimination thresholds actually drop as simulated observer speed increases, reaching about 0.1° at the 30 m/sec (Crowell & Banks, 1993) simulated in our studies. Also, as mentioned previously, theoretical analyses suggest that sensitivity to direction is far more important in determining heading direction than sensitivity to speed (Crowell & Banks, 1996). In summary, it seems unlikely that infants were unable to detect changes in direction of heading information due to some primary limitation on their ability to perceive the speed or direction of moving dots in the display.

Nevertheless, the results from Experiments 1 and 2 leave unanswered the central question about how sensitive young infants are to optic flow patterns that simulate heading directions larger than 16°. The habituation paradigm has certain flaws and is an inefficient way of determining what angles infants can discriminate. Consequently, we developed an FPL technique to measure sensitivity to changes in the direction of self-motion depicted in optic flow patterns. FPL is a standard method in infant visual psychophysics (Teller, 1979). Our modification of FPL involved the simultaneous presentation of two patterns of optic flow. One of the patterns depicted forward and backward motion along an axis parallel to the imaginary line of sight at a 0° heading through a cloud-like array of dots. The other pattern alternated between depicting the same forward and backward motion as described and a novel pattern in which a different angle of motion was depicted. An observer who did not know on which side the changing direction was presented made a forced choice decision about which display side the infant appeared to prefer. By presenting infants with displays of this type and determining whether the proportion of correct judgments varied with heading angle, we sought to more precisely estimate 4-month-olds' abilities to discriminate optic flow patterns. In addition, we sought to boost the likelihood that infants would discriminate displays differing in heading direction by reducing the simulated translational speed and increasing the density of the moving dots. Because Experiment 2 had suggested infants did not discriminate displays depicting 16° changes in heading angle, we elected to test sensitivity to 16°, 32°, and 64° changes.

EXPERIMENT 3

Methods

Participants. Twelve 4-month-old (121–138 days; 6 female) infants recruited as described previously participated. Two additional infants were tested, but their data were not included in the analyses reported because the infants failed to complete at least 20 trials.

Apparatus and display. The apparatus was as previously described. The display consisted of two rectangular regions positioned at the far left and far right of the computer monitor. At the 90-cm viewing distance, each region was 15° (H) by 30° (V), and there was a central blank region 8° in width in which fixation displays appeared. Within each display region, optic flow movies simulating forward and backward motion through a field of star-like points were simultaneously presented. The dots were the same size and luminance as in the previous studies, but the density of dots in the viewing plane was 0.17 dots/deg^2, approximately 50% greater than that used in the earlier studies.

Each optic flow movie consisted of alternating episodes of forward and backward motion in which the direction changed every 1.25 sec. The translational speed simulated was 3.8 m/sec, a speed that approximated a fast running pace. To isolate sensitivity to 180° changes in motion from smaller angular changes, on every other forward/backward cycle, the angle of change depicted in one of the displays varied to a specific nonzero angular heading defined with respect to the anterior–posterior axis. Nonzero heading values for each trial were chosen randomly from a set of six angles (± 16°, ± 32°, and ± 64°). The nonzero displays were displayed on every other cycle beginning with the second one. Statistics describing the optical direction and speed for each of the display conditions are indicated in Table 1. Figure 4 shows a schematic of the display. In addition, QuickTime movies are archived on the *Infancy* Web site at www.infancyarchives.com.

Design. A completely balanced block consisted of 12 trials in which each movie simulating motion along the 6 angles was presented on both the left and right sides of the screen. Within each block trial order was randomized. A single experimental visit consisted of 3 blocks of 12 trials or a total of 36 trials. The events were presented continuously until the experimenter terminated the episode. A typical episode took 5 to 7 min to complete.

TABLE 1
Optical Motion Statistics for Displays in Experiment 3

Heading Condition	*Speed (°/sec)*		*Direction (Degree From Vertical)*	
	M	*Median*	*M*	*Median*
0°	2.6	1.6	n/a	n/a
16°	5.3	3.3	90	90
32°	8.9	5.7	90	90
64°	14.8	9.4	90	90

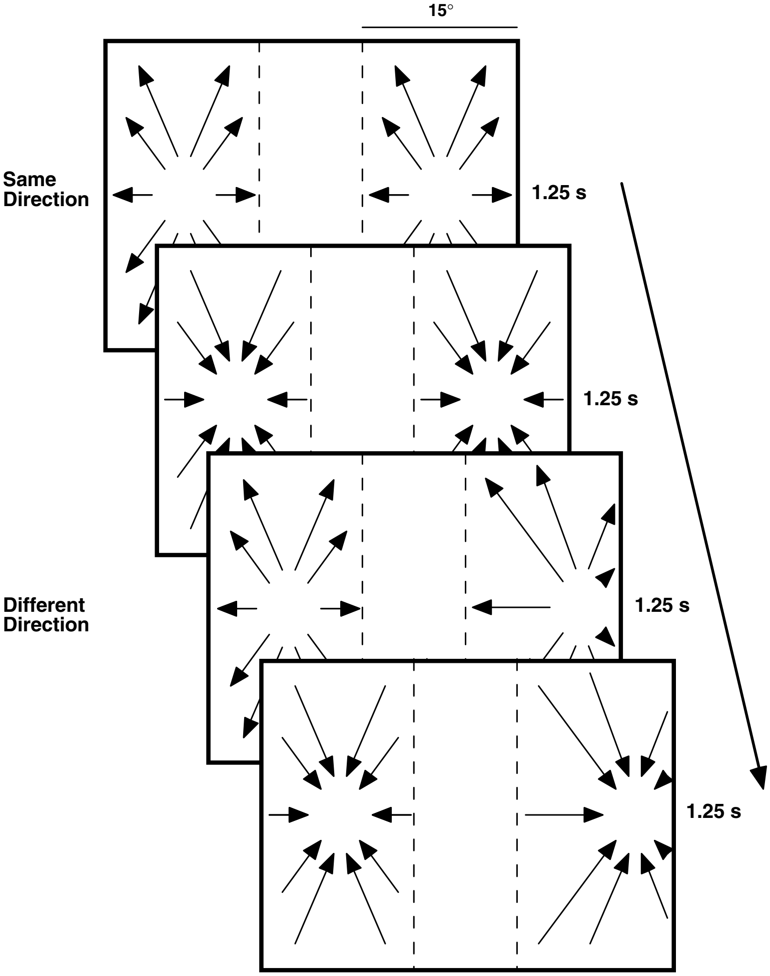

FIGURE 4 Schematic of optic flow display in Experment 4. During one phase (Same Direction), identical optic flow movies depicting forward and backward motion through a cloud of randomly positioned dots were presented in both display regions. In the other phase (Different Direction), the heading angle depicted in one of the display regions changed. The infant observed each of these phases in alternating order, one following the other, until the experimenter made a forced choice decision concerning which side the infant preferred.

Procedure. Informed consent procedures were as previously described. Once the infant was seated in the car seat, the experiment began. The experimenter initiated each trial with a key press. First, a cartoon segment appeared in an 8° (H) × 6° (V) window centered in the monitor for a period of 2 to 3 sec. This was designed to attract the infant's attention to the center of the screen.

The screen went blank and then the two optic flow movies appeared. Both were identical and depicted first forward, then backward motion along the 0° or anterior–posterior axis. At the end of the first forward/backward cycle, 1.25 sec following the start of the movie sequence, the second cycle began in which one of the displays depicted a different, nonzero direction of motion while the other display repeated the forward/backward pattern. The direction of motion depicted alternated between the 0° heading, which was the same as the comparison side, and a different nonzero heading, on every other cycle. At the beginning of the first cycle where one of the displays depicted a different direction, a message appeared to the experimenter indicating that she should choose which side of the display the infant appeared to be orienting toward. The message remained illuminated, and the displays were shown continuously until the experimenter made a forced choice for each trial. Once the choice was made, the screen went momentarily dark, and the experimenter received feedback about whether her choice was correct before the next trial began. As deemed necessary by the experimenter to maintain interest, infants were periodically allowed to view a series of randomly positioned geometric shapes in between experimental trials. If the infant grew fussy or uncooperative, the episode was terminated.

Once the optic flow test was completed, infants were taken to an adjacent room for visual acuity testing to confirm that each infant's vision was within the normal range. Each infant's grating visual acuity was tested using the Teller Visual Acuity Card system. Children sat on a parent's lap in front of a puppet theater behind which the experimenter sat. The parent's view of the infant and the puppet stage was blocked, but infants could see the experimenter through an opening in the stage. The experimenter showed infants a series of gray cards in which high-contrast black and white stripes were positioned at one end or the other. The stripe width varied from high to low, and the experimenter judged on which side the stripes were positioned by observing infants' eye and head movements through peep holes in the center of each card. Once the experimenter had determined the smallest stripe width the infant could reliably detect, that width, in cycles per degree of visual angle, was recorded as the estimate of that infant's visual acuity. Visual acuity estimates ranged from 3.32 cycles per degree to 6.77 cycles per degree with a geometric mean of 4.61 cycles per degree. This confirmed that the individual dots, 0.4° in width, should have been visible to all of the infants in the study.

Data analysis. Proportion correct observer judgment scores for each display condition for each infant were computed. Data were collapsed across conditions that were identical in the magnitude of the heading change simulated and across side of presentation. From these data, group average proportion correct scores were computed for each heading angle condition. In addition, psychophysical functions were estimated for each individual's data by fitting a probit function to the proportion correct data. From these fitted functions, individual 75% correct discrimination thresholds were determined.

Results

Infants completed an average of 34 trials per visit, and the experimenter took an average of 3.9 sec per trial to make a forced choice decision. Figure 5 plots the average proportion correct judgments made by the experimenter for the 16°, 32°, and 64° conditions collapsed across side of presentation and motion. It indicates that mean proportion correct judgments at the smallest, 16° angle was .48 (*SE* = .044), a value not significantly different from chance levels of .5, $t(11) = .479$, *ns*. Proportion correct judgments were larger at the 32° and 64° heading angles, however. Mean proportion correct scores for the 32° condition were .625 (*SE* = .02) and for the 64° condition .667 (*SE* = .044), both of which exceeded chance levels. A repeated measures ANOVA was carried out with the log transformed proportion correct scores with angle as a three-level within subjects factor. That analysis revealed a significant main effect for angle, $F(2, 22) = 8.30$, $p = .002$, confirming that performance differed across the three angle conditions. Post hoc tests of factor level means using the Scheffé correction for multiple comparisons suggested

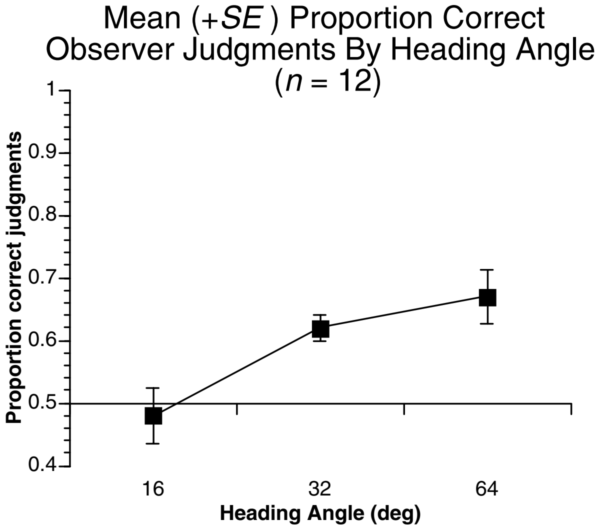

FIGURE 5 Results from Experiment 4. The mean (± 1 *SE*) proportion of correct judgments made by the observer are plotted for each of the three heading angle conditions collapsed across side of presentation.

that the mean proportion correct score for the 16° condition was smaller than the 32° and 64° conditions, $p = .004$.

Individual psychophysical functions were estimated by fitting a probit function to the proportion correct scores. Because a psychophysical threshold can only be meaningfully interpreted under conditions where the fitted slope is positive, indicating increasing observer accuracy as heading angle increased, we focused attention on those infants whose fitted probit functions had positive slopes. Individual psychophysical functions with positive slopes were estimated for 9 of the 12 infants and 75% correct threshold values were estimated from these functions. The geometric mean of the threshold estimates was 54.3°; the minimum and maximum were 39.7° and 66.5°, respectively.

Discussion

The results from Experiment 3 indicate that 4-month-old infants do not discriminate optic flow patterns that depict 16° changes in heading direction, but they do appear to detect larger changes at least some of the time. The average proportion correct judgments in the 32° and 64° conditions exceeded chance levels, and the 75% correct discrimination thresholds estimated from individual infants' data ranged from a low of 39.7° to a high of 66.5°. Thus, in addition to demonstrating the utility of a more sensitive psychophysical procedure, Experiment 3 provides evidence consistent with the results from the previous habituation studies. It appears that failures to detect look time recovery toward 4°, 8°, and 16° changes in heading direction in the previous habituation studies stemmed largely from the fact that 4-month-olds could not discriminate direction changes of this magnitude, at least under the range of stimulus conditions employed in these experiments.

GENERAL DISCUSSION

At an age when infants can discriminate some aspects of object form from motion (Arterberry & Yonas, 2000; Bertenthal et al., 1987; Kellman, 1993), blink, or make backward head movements in response to approaching textures (Nañez & Yonas, 1994), and discriminate between objects and apertures defined by motion and texture information (Schmuckler & Li, 1998), they appear to have only limited capacities to discriminate between optic flow displays that depict changes in the direction of simulated self-motion. The combined results from three studies using two different experimental paradigms strongly suggest that the minimum heading angle 4-month-olds can reliably discriminate is at least 32°. The results do not indicate when optic flow discrimination abilities approach adult levels, but they suggest that aspects of optic flow perception related to the determination of one's direction of self-motion through space may not be especially well developed in young, prelocomotor infants.

Factors Limiting Infants' Performance

There are a number of reasons why these experiments may have underestimated infants' true abilities. First, actual self-movement is accompanied by vestibular and other proprioceptive information about the direction of speed of motion. It is possible, that infants' sensitivity to changes in the heading direction simulated by these displays was diminished because the displays were inconsistent with the infants' own, correct perceptions of the absence of self-motion. However, in laboratory settings with adults, the addition of vestibular or proprioceptive information adds very little to the accuracy of adults' self-motion perception beyond that afforded by visual information alone (Telford, Howard, & Ohmi, 1995). It is possible but somewhat unlikely that infants are more sensitive than adults to this conflict between sensory cues. Data examining whether infants show increased sensitivity to changes in heading direction under conditions where they are actually moving through space would resolve the matter conclusively.

Second, the displays may have presented dots at speeds or with direction changes that were outside of infants' abilities to detect reliably. The processing of motion patterns that vary in speed, direction, and distribution are likely to be crucial for the capacity to distinguish moving objects from the motion of an observer, and to determine precisely one's direction and speed of self-movement (Banton & Bertenthal, 1995, 1997; Banton et al., 2001). Nevertheless, on the basis of previously published data on speed and direction sensitivity to uniformly moving patterns (Banton et al., 2001; Wattam-Bell, 1996), infants should have been able to discriminate the displays depicting the smallest (16°) heading change. The fact that they did not is somewhat surprising given that in many cases, the differences between displays were quite large (see Table 1). The discrepancy serves as a reminder that only a small subset of naturally occurring patterns of optic flow are uniform in speed or direction. Indeed, as previously discussed, the speed and direction gradients contained within optic flow patterns are important sources of information about observer motion and environmental layout. Perhaps young infants have limited abilities to discriminate between optic flow patterns that simulate self-motion because they are less sensitive to these speed and direction gradients than they are to changes in speed and direction in uniformly moving displays. Banton and Bertenthal (1997) argued that there may be distinct motion processing subsystems devoted to different perceptual problems—distinguishing self-motion from object motion, for example—and, that each subsystem may have its own developmental time course. These data might be used to argue that this account should be extended, but for the time being, it is clear that the relationship between low- and high-level motion processing in infants remains poorly understood.

Third, the displays in these studies simulated different directions of self-motion using only the movement of randomly positioned dots that remained a constant size. That is, the rich visual textures and shadows and interposition that are characteristic of locomotion through natural viewing environments were eliminated, and other cues, such as motion parallax, reduced. It is possible that infants discriminate direction of motion information in a more robust fashion in natural, or at least richer, visual environments. Of course, patterns of optic flow are not the only cues to perceiving heading that have been proposed (e.g., Cutting et al., 1992) and tested in adults. But, there is a large body of evidence that optic flow alone is sufficient for discrimination of direction of heading in adults, and in some cases, for steering (e.g., Warren, 1998). There is reason to believe that the integration of multiple visual cues for spatial information takes place over an extended period in postnatal life. Accordingly, it is unlikely that the addition of other sorts of visual information would substantially alter the results presented here. However, we are now conducting studies that will examine this question in detail.

Fourth, it is possible that by presenting infants with relatively narrow optic flow patterns in the central part of the visual field this paradigm underestimated their abilities. For example, there is some evidence that infants in a moving room situation respond most strongly to lateral movement of the side walls (Bertenthal & Bai, 1989), and several investigators have suggested that peripheral visual information dominates postural compensation mechanisms (e.g., Held, Dichgans, & Bauer, 1975). More recent research with adults suggests that not only does optic flow presented in the center of the visual field induce postural sway that is at least as large as peripheral flow (Bardy, Warren, & Kay, 1999; Stoffregen, 1985, 1986), but that judgments of heading are somewhat more accurate with radial flow fields presented in the center of the visual field, such as the kind presented in the current infant studies, than lamellar flow fields presented in the periphery, such as those typically generated in the moving room (Crowell & Banks, 1993). Given that an enlargement of the effective visual field is one of the characteristic patterns of early visual development (e.g., Maurer & Lewis, 1991), it is unlikely that presenting optic flow patterns in the periphery would have improved infants' performance in the current experiments. Whether larger displays would improve performance is an open question.

Fifth and finally, these studies leave unresolved the question of how the visual discrimination of optic flow patterns is related to the use of optic flow to guide locomotion or maintain balance that the moving room studies, for example, appear to require. It is possible that visual discrimination of optic flow patterns and the use of optic flow to control posture are subserved by functionally separate systems that have different developmental time courses. Accordingly, young infants might show greater sensitivity to changes in optic flow direction using a physical measure such as body sway than visual discrimination measures such as direction or duration of looking. Studies in adults suggest that the angle of body sway does change in accordance with changes in the simulated angle of self-motion (Bardy et al., 1999). However, these studies also suggest that it may be quite difficult to detect small (< 30°) changes in body sway due to biomechanical factors and the noise inherent in the posture signal. Detailed data of these kind in infants do not yet exist, but it is likely that small systematic changes in body position in response to small changes in heading angle would be especially difficult to detect in infants. Accordingly, visual discrimination measures like those used in our experiments may be the most sensitive measures available for studying optic flow processing in young infants.

Implications

These results provide evidence that prelocomotor infants can discriminate optic flow patterns that simulate self-motion in different directions, but that visual sensitivity to the magnitude of direction change is relatively poor. These studies leave two basic questions unanswered. One is how sensitivity changes over the next several months of life. The other question concerns what factors influence the development of adult-like sensitivity. We are addressing the first question in ongoing research, but the current results suggest that substantial development must occur. With regard to the second question, there are two likely factors influencing these patterns of change that merit mention.

One factor is locomotor experience. Locomotor experience plays an important role in shaping young animals' abilities to perceive and act on some forms of visual information about spatial relations, including some aspects of optic flow (Adolph, 1997; Adolph, 2000; Bertenthal & Bai, 1989; Bertenthal, Campos, & Kermoian, 1994; Bertenthal et al., 1997; Held & Hein, 1963). In contrast, locomotor experience may not influence the emergence of sensitivity to other spatial variables such as linear perspective or texture gradients (e.g., Arterberry, Yonas, & Bensen, 1989). Four-month-old infants do not generate significant amounts of translational optic flow by means of their own self-movement. Consequently, sensitivity to this sort of pattern of motion may be relatively poor until infants begin to sit erect or crawl, thereby creating regular opportunities to perceive behaviorally relevant patterns of optic flow and tune perception and action systems accordingly. At the same time, the current results suggest that passive visual experience might play an as-yet-unexplored role in shaping infants' perceptual preferences because infants clearly discriminated between displays that depicted changes in direction they would only have experienced passively. Clearly, additional research on the question of what roles passive and active experience jointly play in shaping the perception of information about self-motion is essential.

Another factor that may play a role in contributing to ongoing development in the discrimination of heading direction is neurological development. There is limited anatomical or physiological data about the development of neural systems for optic flow processing, specifically the motion processing circuits of the posterior temporal and parietal lobes. Nevertheless, the existing evidence suggests that increases in metabolic levels (Chugani, Müller, & Chugani, 1996; Chugani, Phelps, 1986) are somewhat delayed in these areas relative to those in primary visual cortex in which peaks of synaptogenesis appear to occur between 4 and 6 months (Huttenlocher, 1990; Huttenlocher & Dabholkar, 1997). Accordingly, it is possible that the functional immaturity in cortical circuits that specialize in complex motion processing may provide biological constraints on young infants' abilities to detect certain aspects of optic flow. Indeed, other investigators have argued that the development of other aspects of spatial processing, such as the emergence of head or body-centered representations for guiding eye movements (e.g., Gilmore & Johnson, 1997a, 1997b), may be fundamentally linked to patterns of cortical maturation in functionally related visual processing circuits.

In conclusion, we have provided data that are the first of their kind to quantitatively describe young infants' sensitivity to changes in optic flow patterns that simulate different directions of observer heading. The results of three different experiments using two different experimental paradigms, including a novel adaptation of FPL, converge on the same basic conclusion: Young infants discriminate optic flow patterns that simulate only large (> 32°) changes in the direction of self-motion. This suggests that prior to the onset of locomotion, infants process patterns of optic flow but only to a limited extent. We hypothesize that the emergence of more precise adult-like abilities to discriminate between optic flow patterns may have a prolonged developmental time course due to the joint influence of perceptual, experiential, and neurological factors. When adult-like sensitivity emerges and what specific factors influence its emergence remain challenges for future research.

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