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Infant direction discrimination thresholds

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Abstract

Although adults can detect direction differences as small as 1 arc degree, the ability of infants to discriminate direction of motion is less clear. This study measures the precision with which 6-, 12-, and 18-week-old infants discriminate direction of motion. Infants viewed random dot kinematograms in which a direction difference between the target and background dots defined a circular target. The target was then placed into continuous motion. An FPL paradigm was used to assess infants' preference for the target as a function of the direction difference between the target and background dots. Direction discrimination thresholds with a moving target were indeterminate at 6 weeks of age, 22° at 12 weeks of age and 17° at 18 weeks of age. This precision was maintained across different testing conditions. However, performance dropped markedly when dot motion was presented within a flickering stationary target. It was concluded that infants can make relatively fine discriminations of motion direction if given an engaging stimulus.

Keywords: Development; Infant vision; Relative motion; Direction

1. Introduction

Motion provides information for accomplishing a broad range of fundamental functions including the encoding of depth, the estimation of the time until collision with an approaching object, the segmenting of a figure from its background, the control of posture, and the initiation of eye movements (Nakayama, 1985). This constant reliance on motion suggests that the development of motion sensitivity is a critical part of normal development. Progress has been made in understanding how the ability to sense motion develops (see Braddick, 1993; Banton & Bertenthal, 1997 for reviews), but there are still several aspects of infant motion sensitivity where very little is known. One of these topics is how infants develop the ability to discriminate different directions of motion.

Existing studies of infant direction discrimination are limited to the case where direction of motion differs by 180° (i.e. opposite directions). One of the earliest pieces of evidence that infants are sensitive to opposite directions of motion comes from studies of optokinetic nystagmus (OKN). These studies demonstrate that infants make directionally appropriate eye movements to leftward versus rightward motion (e.g. Dayton, Jones, Aiu, Rawson, Steele, & Rose, 1964; Kremenitzer, Vaughan, Kurtzberg and Dowling, 1979; Atkinson & Braddick, 1981). The eye movement data are complemented by results from other infant behavioral paradigms, such as forced-choice preferential looking (FPL) and habituation. In an FPL study, Dannemiller and Freedland (1991) demonstrated infant sensitivity to opposite directions of motion by presenting infants with two side by side columns of horizontal stripes, both of which oscillated up and down in unison. When a single stripe was oscillated in counterphase to the other stripes, 8-week-old infants preferred to look at the side containing the stripe in counterphase. Using a similar 'relative motion' paradigm, other investigators have used random dot stimuli to better isolate motion sensitive mechanisms from position sensitive mechanisms (for details regarding the isolation of motion mechanisms, see Nakayama and Tyler, 1981). In FPL studies that used random dot stimuli, infants preferred

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opposing directions of motion to uniform motion at 10 weeks (Wattam-Bell, 1996a) and 13 weeks (Bertenthal & Bradbury, 1992) of age. In addition, results from summation-at-threshold experiments further demonstrate that 3-month-old infants possess motion mechanisms tuned for opposite directions (Dobkins & Teller, 1996). Corroborating these FPL studies, Wattam-Bell (1996b) used a modified habituation procedure to demonstrate infant sensitivity to opposite directions of motion. He habituated infants to a field of uniformly moving random dots. Following habituation, infants were simultaneously presented with two displays. One contained the same uniform motion shown during habituation while the other contained opposing motions. Six- to 8-week-old infants looked significantly longer at the opposing motion, while 3–5-week-old infants looked equally at the two displays. Finally, these behavioral data are supported by the results from visual evoked potential (VEP) studies, which demonstrate sensitivity to opposite directions of motion within the first two months of life (Wattam-Bell, 1991; Hamer & Norcia, 1994). In sum, these studies show that infants begin to discriminate opposing directions of motion between 6 and 10 weeks of age.

With regard to the discrimination of directions separated by less than 180°, a single study has demonstrated that the direction of infant optokinetic nystagmus can be accurately judged when the stimulus direction is varied in 45° increments (Manny & Fern, 1990). Such results indicate that 1-, 2-, and 3-month old infants can discriminate direction to within 45°. Because measuring directional discrimination was not the focus of the Manny and Fern study, and since previous infant studies tested sensitivity only for *opposite* directions of motion, the precision with which infants can discriminate two directions of motion has yet to be tested directly. It is known from adult studies that the motion system has the capability of discerning direction differences as small as 1–2° arc (de Bruyn & Orban, 1988). Thus, by studying the development of this capacity in infants, one can track the development of directional mechanisms. To this end, direction discrimination thresholds were obtained in infants between 6- and 18-weeks of age. The results of these experiments demonstrate a large improvement in the ability to discriminate fine direction differences between 6- and 18-weeks of age. Whereas thresholds could not be obtained at 6-weeks, 18-week-old infants could discriminate direction differences of 17°.

2. Experiment 1 (precision of direction discrimination with moving targets)

The first experiment measured the precision with which infants could discriminate direction of motion. Direction discrimination thresholds were obtained using directional differences between the target and background while the target itself was in continuous motion (Fig. 1). It was anticipated that the target motion would attract infants' attention and thus improve performance.

2.1. Subjects

A total of 72 infants participated in Experiment 1 at the University of Virginia. Eleven infants were 6 ± 1 weeks of age, 29 infants were 12 ± 1 weeks of age, and 32 infants were 18 ± 1 weeks of age. Infants were recruited from birth announcements in the local newspaper.

2.2. stimuli

To measure direction discrimination, a modified version of the opposed motion stimuli of Bertenthal and Bradbury (1992) and Wattam-Bell (1994) was used. Whereas these original studies employed 'direction-defined' regions of space in the form of oppositely-moving (i.e. 180° direction difference) strips of random dots, the present study used stimuli that differed in direction by various degrees (between 8 and 180°). Specifically, the stimuli were random-dot kinematograms consisting of a field of moving dots divided into a background and a small circular sub-region. The direction of dot motion in the background and the circular sub-region were controlled independently. When the background and circular sub-region were assigned different dot directions, the directional difference produced a motion-defined circle (i.e. the 'target'), that was placed on either the right or left side of the display in a FPL paradigm. The directional difference between the target and background dots was varied in order to obtain direction discrimination thresholds. The background dots continuously drifted vertically while

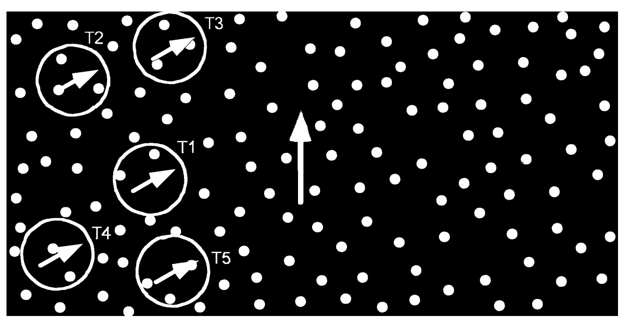

Fig. 1. The continuously moving stimuli. Random-dot motion is represented by arrows. The displacement of the circular target over time is represented as T1–T5 to indicate the sequential target positions. Because the target was defined by direction of motion, circular outlines were not present in the actual stimuli. Note that the apparent motion of the random dots and the circular target are distinct.

the target dots drifted in a direction that differed from vertical by 0, 8, 16, 23, 34, 45, 90 or 180°. The target subtended 7.4° in diameter against a 25° × 40° background. Each dot subtended 4.5 × 4.5 arc min and had a luminance of 13.8 cd/m^2. The dots were randomly distributed on a 0.012 cd/m^2 background with a density of 10%. Dots were put into motion by displacing them 0.52° every 48 ms to produce a dot speed of 11°/s. Dot lifetime was unlimited.

Because preliminary attempts to use this method often did not result in preferential looking (i.e. infants seemed to enjoy viewing both the target and non-target sides of the display), another dimension was added to the stimulus; the target itself was placed in apparent motion. This made it appear (to adult observers) like a continuously moving circle on either the left or right side of the display (see Fig. 1). The circular direction-defined target was sequentially displaced every 500 ms, through five pseudo-random positions presented on either the left or right side of the display (as mirror images). The sequences were looped indefinitely to produce continuous motion. The critical aspect of these stimuli was that the moving circle was seen only if it could be differentiated from the background based on the different directions of random dot motion. This manipulation greatly enhanced infants' preference for the target side of the display, allowing one to obtain reliable direction discrimination thresholds. In addition, this configuration allowed one to evaluate the effectiveness of the new stimulus design, which may be useful in future infant discrimination experiments unrelated to motion direction per se.

2.3. Apparatus and procedure

Stimuli were presented on a 29 in. video display monitor (Mitsubishi XC-2930C) under the control of a ZEOS 486 computer. The stimulus monitor was located at the back of a matte black viewing chamber to minimize distractions to the infants. Diffuse light was shone from below the stimulus monitor to allow infant eye and head movements to be viewed with a video camera positioned between the light source and the stimulus monitor. The camera image was shown live on a response monitor placed above the viewing chamber. This apparatus has been described previously (Banton & Bertenthal, 1996).

During testing, infants were held approximately 60 cm from the stimulus monitor and the room lights were turned off. Six-week-old infants viewed the stimuli from a modified car seat that was held by a parent. This helped to stabilize their head position. Older infants viewed the stimuli from a sitting position in the parent's lap. The parent could not see the stimuli during testing. On each trial, the computer randomly selected and displayed one of 16 stimuli (eight direction differences by two target positions [left or right]). As the infant viewed the display, a trained observer watched the infant on the response monitor and judged if the infant preferred to look toward the left or the right side of the display. The observer was given an unlimited amount of time to make a judgement, but judgements were typically made after the infant looked for 5–10 s. The trial ended when the observer guessed which side the infant favored. The observer was then told which side had contained the target. Testing continued until the infant completed 20 trials per direction difference or could not continue due to fussiness, sleep, or other factors promoting inattentiveness to the display.

The large number of stimuli being studied required that infants either receive a subset of stimuli or that they return for multiple visits to complete testing. In Experiment 1, infants received a subset of the full stimulus set. Infants generally saw four of the 16 stimuli (two direction differences by two target positions). A subgroup of 12-week-old infants ($n = 8$) saw six different stimuli because 12-week-old infants initially seemed to exhibit greater interest in the stimuli than the other age groups. Another subgroup of 12-week-old infants ($n = 9$) was presented with only the two 23° stimuli to provide additional data at this critical value. The stimuli were selected pseudo-randomly, since some direction differences from the original stimulus set were not considered. For example, 6-week-old infants were not shown small direction differences since pilot testing indicated they would be unlikely to discriminate these stimuli. Furthermore, 12-week-old infants were not shown the 90° direction difference because this was added to the stimulus set after 12-week-old testing had begun and it appeared unlikely to influence their threshold. When selecting stimuli, sessions in which all of the chosen direction differences were likely to be below threshold were excluded so that infants would not become overly frustrated with the task. Direction discrimination thresholds were calculated for the 6-, 12-, and 18-week-old groups.

2.4. Data reduction

The proportion of trials on which the observer made a correct judgement was calculated for each direction difference. Trials from all infants were pooled to form a grand mean for each direction difference. In effect, the grand mean weighted each infant's contribution by the number of trials they completed. This was done because the number of trials completed by each infant varied greatly, so the grand mean reduced variability that could arise from individual infants who completed a low number of trials. Standard errors of the mean were calculated from the between subjects estimate of variance. Direction discrimination thresholds were then calculated by plotting the grand means for each direc-

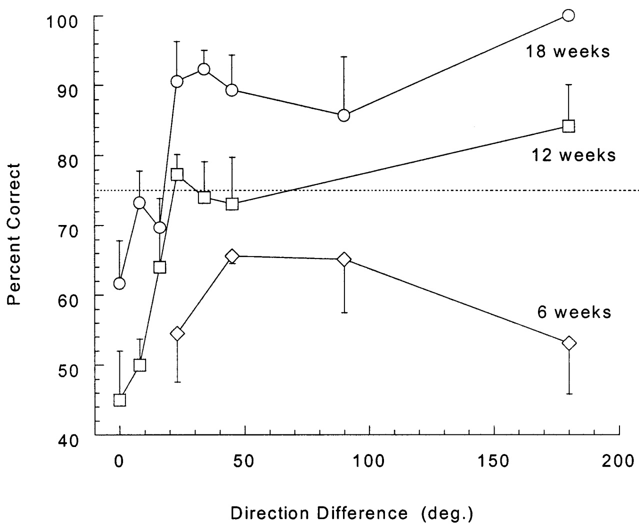

Fig. 2. Performance (percent correct) as a function of the direction difference between the target and background of the random dot motion display. Performance improved with age. Direction discrimination thresholds at the 75% correct level (gray line) were obtained by 12 weeks of age.

tion difference and interpolating to the 75% correct level. In practice, performance was within 5% correct of the means calculated from equally weighted data, so the overall pattern of performance did not vary with the reduction method.

2.5. Results and discussion

Fig. 2 shows the observer's mean proportion correct with continuously moving targets. Six-week-old infants failed to reach a 75% correct threshold, and performance was above chance ($\alpha = 0.0125$ following a Bonferroni correction for multiple tests) only for a direction difference of 45° [$t(3) = 16$; $P < 0.0125$]. Twelve-week-old infants reached the 75% correct threshold when direction differed by 22°. Eighteen-week-old infants reached this threshold when direction differed by 17°. Thus, direction discrimination improved with age and reached a much finer precision than previously measured.

Although one might assume that 6-week-old infants failed to reach threshold because the individual target dots were below their acuity limit, previous work shows that 6-week-old infants viewing dots of this size can judge their direction of motion with 90% accuracy (Banton & Bertenthal, 1996). Therefore, acuity does not limit motion perception in this case. Why then are 6-week-old infants so poor at making direction discriminations in the present experiment if previous research shows that they can accurately judge direction of motion? It is argued that this is due to task differences. Banton and Bertenthal (1996) used an optokinetic response to measure the *detection* of random dots moving uniformly across a display screen. However, the present experiment measured the ability of infants to *discriminate* two directions of motion. Previous work shows that the detection and discrimination of motion develop differently, consistent with the idea that infants are able to detect motion before they can discriminate two directions of motion (see Banton & Bertenthal, 1997 for a review).

Informal observation showed that adults could discriminate the target from the background when the direction difference was 0°. This was due to their sensitivity to the accretion (appearance) and deletion (disappearance) of dots along the edge of the circular target window. Since infants gain sensitivity to accretion and deletion by 5 months of age (Granrud et al., 1984) or earlier (Kaufmann-Hayoz, Kaufmann, & Stucki, 1986), infants' performance on the direction discrimination task could be confounded by this emerging sensitivity. The 0° direction difference served as a control for this possibility. If infant performance was based only on sensitivity to direction differences, then performance should be at chance when the target and background had identical dot directions. Performance at 0° was not significantly different from chance at any age tested [$t(2)_{12\text{weeks}} = -0.996$, $P = 0.424$; $t(3)_{18\text{weeks}} = 1.467$, $P = 0.239$], confirming that extraneous cues from accretion and deletion were negligible in this task. Even so, the 18-week-old infants were correct 62% of the time, perhaps hinting at the impending emergence of sensitivity to accretion and deletion.

3. Experiment 2 (precision of direction discrimination with flickering stationary targets)

The results of Experiment 1 demonstrated that our stimulus configuration (Fig. 1) elicited reliable looking responses in infants. From pilot experiments, we had reason to believe that it was the continuous *motion* of the direction-defined target that was particularly effective in capturing infants' attention. To test this, thresholds were obtained for four additional 18-week-old infants when the direction-defined target remained *stationary*, but flashed on and off at 0.4 Hz. The comparison between moving and flickering stationary targets allowed us to assess which stimulus type produced better performance.

3.1. Stimuli

As in Experiment 1, the background dots moved vertically, and the direction difference between the target and background dots was varied. However in Experiment 2, the target remained in one position (i.e. it was not continuously moving as in Experiment 1) and the dot motion within the target region oscillated at 0.4

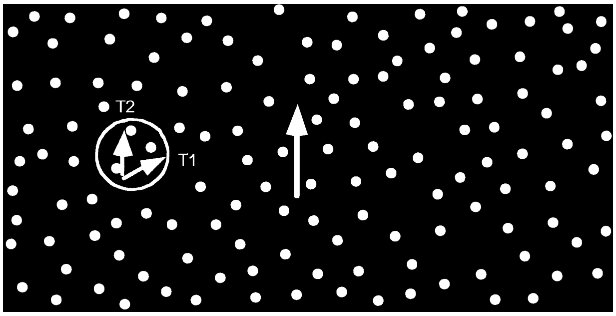

Fig. 3. The stationary stimuli. Random dot motion is represented by arrows. The target is represented as a circle. The dots within the stationary circle oscillated between the background direction (T2) and a unique direction (T1) at 0.4 Hz.

Hz between motion in the pre-selected direction and vertical motion (Fig. 3). The oscillation made the target appear to flash on and off, since the target simply blended into the background (and went 'off') when its motion was vertical. This *flashing* method was added because pilot experiments indicated that the flashing made the stimulus somewhat more attractive to infants than a continuously presented stationary target.

The apparatus and procedure were unchanged except that each infant received three pre-selected direction differences (22, 31, and 45°) instead of two.

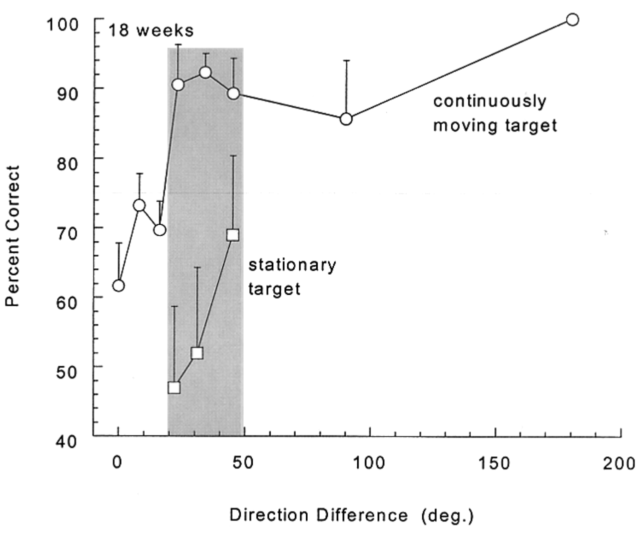

Fig. 4. Direction discriminations for continuously moving and stationary targets in 18-week-old infants. Performance was superior when the circular target was continuously moving (from Fig. 2) as compared to when it was stationary. Data falling within the gray region were used in the statistical analysis of moving vs. stationary stimuli.

3.2. Results and discussion

Fig. 4 compares performance with stationary flashing targets to performance with continuously moving targets from Experiment 1. Clearly, performance with moving targets is higher than performance with stationary targets. Performance with stationary targets improved slightly toward that with moving targets as direction difference increased, but a 75% correct threshold was never reached using a stationary target. Thus, continuously moving targets are more attractive to infants than stationary targets, even when the stationary targets are made more salient by flashing them on and off.

To test these different statistically, direction different from Experiments 1 and 2 that were essentially identical (23 and 22°; 34 and 31°; 45 and 45°; respectively) were compared using multiple t-tests. The effect of target type was significant at the 31° direction difference $[t(19)_{31^\circ} = -3.623,\ P < 0.017]$ where the largest number of infants was tested. It was suspected that the difference between moving and stationary targets would be borne out for direction differences of 22 and 45° if more than seven infants had been tested in these conditions $[t(5)_{22^\circ} = -3.146,\ P = 0.026;\ t(5)_{45^\circ} = -1.687,\ P = 0.152]$.

4. Experiment 3 (individual sensitivity to direction differences)

It was hoped that the direction discrimination thresholds obtained in Experiment 1 would be robust enough that the moving target technique could be used in a variety of experimental situations. To extend the findings from infants tested on a subset of conditions in a single session, a small group of infants was selected who would be tested on all conditions across multiple sessions.

4.1. Subjects

Six infants who were 12 weeks of age (± 1 week) participated. Each infant was tested in three to four sessions at UCSD. Extensive individual testing provided a more detailed look at individual performance and it allowed us to evaluate the success of the stimuli under slightly different testing conditions.

4.2. Stimuli and apparatus

In this experiment, the stimuli were motion-defined circles that moved continuously. They were identical to the stimuli in Experiment 1 (see Fig. 1). The apparatus consisted of a 21 in. Nanao-F2-21 monitor controlled by a Gateway P5-133 personal computer.

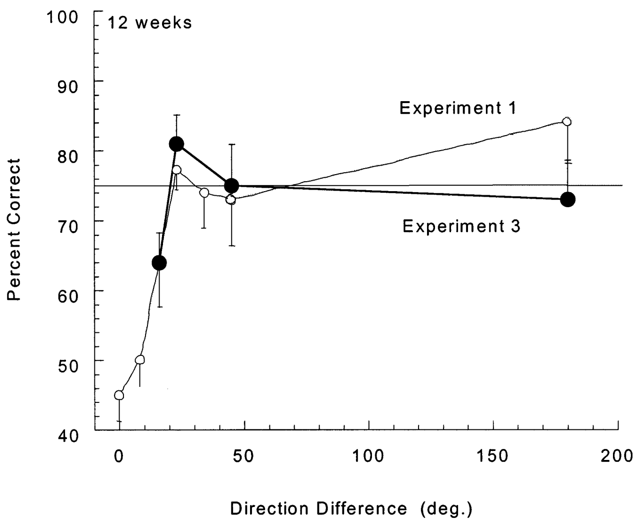

Fig. 5. Direction discriminations made by 12-week-old infants who were tested on all conditions over two to three sessions compared to those who were tested on a subset of conditions in a single session (from Fig. 2). The data are similar across different experimental designs.

4.3. Procedure

The testing conditions were identical to those employed in Experiment 1, except for the following: (1) Infants were held slightly closer to the monitor (53 vs. 60 cm). This was required to produce the same stimulus sizes and speeds as in the original experiment. (2) Infants were held up to the display by the experimenter, who monitored the infant's gaze behavior via a camera and made decisions about the location of the target after each trial. Feedback about the correctness of each response was provided by the parent, who also recorded the experimenter's responses via keyboard presses. (3) Each infant was tested on four different direction differences (16, 23, 45 and 180°). As in experiments 1 and 2, the observer was given an unlimited amount of time to make a judge-ment, but judge-ments were typically made within 5–10 s. We attempted to obtain 80 trials from each infant (20 trials/condition). Two of the six infants did not finish the entire experiment due to fussiness or sleepiness. These infants completed 48 and 62 trials.

4.4. Results & discussion

The results from Experiment 3 are plotted in Fig. 5. The 75% correct threshold for unlimited lifetime dots was 21°. As can be seen in the figure, this is very similar to the 12-week-old threshold of 22° found in Experiment 1. It appears that performance with a moving target is relatively stable across experimental testing conditions.

5. General discussion

There are two main findings from this study. First, infant performance was improved significantly during measures of direction discrimination by utilizing circular targets that moved continuously. The continuous motion seemed to enhance attention to the target, thus improving performance. Flickering a stationary target on and off was much less successful in capturing infants' attention. Target motion might be useful for improving infant performance in many testing situations, since target movement can be applied to other types of stimuli and to methods other than FPL. It was concluded that continuously moving a stimulus is a useful adjunct to current infant testing procedures.

Second, it was found consistently that infants can make relatively fine direction discriminations, on the order of 20° arc by 12 weeks of age and slightly better by 18 weeks of age. This represents the first indication that infants can make such fine direction discriminations. Furthermore, the result was consistent across different laboratories using different experimental designs.

One issue that requires scrutiny is the possibility that the task was actually one involving orientation discrimination rather than direction discrimination. Regan (1986) pointed out that either a physical or a physiological persistence of random dot motions would leave elongated streaks oriented along the direction of dot motion. This can be used to obtain the direction of dot motion (Geisler, 1999). Thus, orientation differences between streaks arising from the different directions of dot motion in the present stimuli could potentially be used to make the discriminations if there was significant image.

Certainly. Persistence infant orientation mechanisms are sensitive enough to account for the present data, since orientation discrimination as precise as 1.33° has been reported for 3-month-old infants (Manny, 1992). Yet even if oriented streaks form during stimulus viewing, the streaks will not be long enough to reach the precision of orientation discrimination needed to explain the current results: Infants' temporal resolution is relatively adult-like, on the order of 45 Hz by 6 weeks of age (Regal, 1981). Thus, 6-week-old infants can resolve periodic luminance changes occurring within a 22 ms period. Given that the present stimulus updated every 48 ms, infants have ample temporal resolution to avoid smearing together multiple frames of apparent motion. Furthermore, adults who viewed these displays were unaware of oriented streaks and subjectively did not feel that they discriminated based on orientation differences. Even if infants smeared the dot motion slightly, orientation still could not account for the present data. Assume that infants smeared 2–3 frames of motion to form streaks of 1° in length. Infants' orientation discrimination using lines that are 1° long shows that they cannot discriminate a 90° orientation difference until 5–6 months of age (Rieth & Sireteanu, 1994). Thus, orientation discrimination with short lines is poorer than the direction discriminations made in the present study. To reach the level of precision obtained by Manny (1992), gratings were used which filled a circular aperture of approximately 9° in diameter. While these arguments are not definitive, they suggest that it is unlikely that the most sensitive mechanism for making these direction discriminations is based on orientation cues. Further research is needed to address this question directly, but based on the available evidence it is concluded that orientation is not being used for these discriminations.

If it is accepted that orientation does not contribute to direction discriminations, the results of the present study add new pieces to the puzzle of how infants develop the ability to detect and discriminate motion. Infants seem to demonstrate uniform motion sensitivity from birth (Tauber & Koffler, 1966; Kremenitzer et al., 1979; LaPlante et al., 1996), although this could be confounded with position sensitivity. By 6 weeks of age however, it is clear that infants are highly sensitive to uniform motion (Banton & Bertenthal, 1996; Banton, Bertenthal, & Seaks, 1999). In contrast, infants do not even begin to gain sensitivity to differential motion until 6–8 weeks of age (Dannemiller & Freedland, 1991; Wattam-Bell, 1994). The present study makes it clear that once sensitivity to differential motion is established, the precision with which it can be discriminated improves with age. There may be several reasons for this improvement in direction discrimination:

(1) Direction discrimination may improve if the range of directionally selective motion mechanisms increases with age. For example, if infants possess a complement of direction mechanisms tuned to only a few directions, discrimination might be poor until mechanisms sensitive to other directions develop. On the one hand, an asymmetrical representation of motion direction is supported by the presence of a monocular asymmetry in OKN for young infants: Temporal to nasal motion elicits OKN but nasal to temporal motion produces little OKN. This asymmetry gradually subsides after 2 months of age, as would be expected when all directions of motion gradually become represented. On the other hand, Hatta et al. (1998) found a symmetrical representation of direction of motion even in the youngest infant monkey V1 neurons. If this result is found in other cortical areas involved in OKN control, then directional asymmetries may be negligible, thus posing a problem for this hypothesis (but cf. Braddick, 1996, for a discussion of the possibility that area MST underlies the motion asymmetry).

(2) Direction discrimination may improve if the bandwidth of directionally selective motion mechanisms narrows with age. According to this hypothesis, the precision of infant direction discrimination should be poor when the bandwidth is wide, because small direction differences will produce similar (indistinguishable) signals in a given detector. Precision should approach adult levels as the bandwidth narrows with age. Hatta et al. (1998) showed that bandwidth does narrow with age. They made physiological recordings from infant Macaque V1 neurons which showed that direction selectivity in 1-week-old monkeys was absent or very broad, approached 45–90° by 2 weeks of age, and reached 30° by 4 and 8 weeks of age. These results lend some support to this hypothesis for the development of direction discrimination.

(3) Finally, direction discrimination might improve if a neural substrate for *making comparisons* between different directions of motion is developing. In a hierarchical scheme of motion processing, this represents the development of a second-order processing site, where the outputs of simple motion detectors are compared in order to extract differential motions. Note that hypotheses 1 and 2 are based on the development of simple motion detectors while hypothesis 3 reflects the development of differential motion detectors.

Striate layer 4B neurons exhibit extensive horizontal connections (Fisken, Garey, & Powell, 1975; Rockland & Lund, 1983) which may be involved in the elaboration of large surround mechanisms that would make these neurons well suited for detecting relative motion (Allman, Miezin, & McGuinness, 1985). Striate layer 4B is thought to become functional between 1 and 3 months of age (Johnson, 1990), matching the onset of direction discrimination near 1.5–2 months of age (Dannemiller & Freedland, 1991; Wattam-Bell, 1994). The parallel development of relative motion mechanisms and direction discrimination suggests a possible relation between the two. Future research may be able to differentiate among these three hypotheses of the development of direction discrimination.

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