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Young Infants' Sensitivity to Motion Parallax

CLAES VON HOFSTEN
Umeå University

PHILIP KELLMAN
Swarthmore College

JORMA PUTAANSUU
Umeå University

Three experiments examined the sensitivity of 3½-month-old infants to motion parallax. While seated in a moving infant chair, infants were habituated to a display consisting of three vertical rods aligned in the fronto-parallel plane. The outer rods were stationary and the middle rod moved contingently with the infant chair. After habituation, two stationary test displays were shown in alternation. In Experiment 1, one test display was spatially identical to the habituation display but corresponded to different retinal motions (three aligned stationary rods). The other test display was spatially different from the habituation display but corresponded to identical retinal motions (a triangular configuration of rods). The results suggest that the difference in retinal motion was detected and responded to. As the magnitude of the contingent retinal motion was only 0.32 deg/s, the results show that young infants are quite sensitive to such retinal change. Experiment 2 was identical to Experiment 1, with the exception that the speed of the infant chair was decreased 50%. Under these conditions, contingent motion was not detected. Experiment 3 asked whether the contingency of the motion was detected or just the motion itself. Both test displays were such that the magnitude of the retinal motion of the middle rod was the same as in the habituation display. However, in one it moved with the infant as for the habituation display (displaced backward), but in the other it moved against the infant (displaced forward). The results indicated that the subjects detected that difference in contingency. Implications of the results are discussed.

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infant motion perception space perception habituation vision

When an observer moves through space, the optical change associated with points in the environment depends on their distance from the observer. The depth information provided by such changes is traditionally called motion

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Correspondence and requests for reprints should be sent to Claes von Hofsten, Department of Psychology, Umeå University, S–90187 Umeå, Sweden, or to Philip Kellman, Department of Psychology, Swarthmore College, Swarthmore, PA 19081.

parallax (Helmholtz, 1925) or motion perspective (Gibson, 1950). Motion parallax is an important source of information about depth in a structured environment. It constitutes a gradient which is not dependent on structural regularities in the environment like parallel lines or equal size units of texture. It is well known that adults use motion parallax in perceiving the spatial layout of the environment (Eriksson, 1972; Gibson, Gibson, Smith, & Flock, 1958; Johansson, 1973; Rogers & Graham, 1979). Rogers and Graham (1979) demonstrated a remarkable sensitivity to this source of information. They used a random-dot pattern on an oscilloscope screen which was transformed by each movement of the observer or movement of the display oscilloscope to simulate the relative motion information produced by a three-dimensional (3-D) surface. They found that under these conditions the sensitivity of the visual system to motion parallax is remarkably high, comparable to the sensitivity to retinal disparity.

Little is known about when children become sensitive to motion parallax. The question is, however, of considerable interest. The importance of motion and change for monocular space perception in adults (e.g., see Johansson, von Hofsten, & Jansson, 1980) argues for an inherent sensitivity to such variables. Furthermore, earlier research indicates that sensitivity to motion and change as information about depth appears very early in development and might play a crucial role in the emergence of space perception in infancy. The purpose of the present study was to investigate some of the basic requirements for a functioning motion parallax system in young infants.

Already at 3 to 5 months of age, infants show a variety of motion perception abilities. Yonas, Petterson, Lockman, and Eisenberg (1980) demonstrated that 3-month-olds blinked and withdrew the head at an optical expansion, but only if it accelerated geometrically and filled large (100°) visual fields. Such "explosive" magnification patterns signify approaching objects when collision is imminent. Carroll and Gibson (1981) found that infants of the same age withdrew the head from an approaching object but not from an approaching aperture. Kellman, von Hofsten, and Soares (1987) found that 4-month-olds generalized the motion of three dots moving toward and away from a common point to the motion in depth of a triangle. Expansion and contraction is by no means the only motion information studied. For instance, Kellman (1984) found that 4-month-olds perceived the 3-D form of a rotating object whose shape was specified by kinetic information, and Granrud et al. (1984) found that 5-month-old infants are sensitive to accretion and deletion of texture as information about depth at an edge. These data suggest that depth perception from motion emerges earlier in development than depth perception from pictorial information. Yonas and associates (e.g., see Yonas & Granrud, 1985) have shown that pictorial depth perception does not emerge until sometime between 5 and 7 months of age.

Furthermore, Yonas, Arterberry, and Granrud (1987) found that disparity-sensitive 4-month-olds would generalize a display in which the 3-D shape of an object was specified by kinetic information to a random-dot sterogram of the same shape. In other words, all infants sensitive to binocular disparity were also sensitive to kinetic information about shape. There are actually data that suggest that space perception from motion may emerge before stereopsis. Yonas, Petterson, and Lockman (1979) found that infants as young as 1 month of age blinked more to an optical expansion than to an optical contraction. Gibson and Walker (1984) presented evidence that infants at the same age were able to perceive the rigidity or elasticity of objects from optical change. These results are remarkable in the sense that they indicate that kinetic information may be the first information to which infants respond in perceiving spatial properties. Sensitivity to binocular disparity emerges between 3 and 5 months of age as demonstrated by a number of investigators (Birch, Gwiazda, & Held, 1982; Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980).

Depth within a spatial structure, which moves relative to the subject or which the subject moves relative to, is specified by its differential retinal velocities. Depth within a structure is what Rogers and Graham (1979) studied, and it is also the focus of the present article. It can be noted that Rogers and Graham obtained the same effects, whether it was the subject that moved relative to the display oscilloscope or the oscilloscope that moved relative to the subject.

Absolute distance from the subject to an object, however, can only be extracted from motion parallax under restricted conditions. During observer motion, the relation between subject motion, the distance to an individual object, and the object's motion are intrinsically ambiguous. Two of the parameters need to be specified to determine the value of the third one. For a specific subject motion, an optical motion can correspond to a moving object at one distance or a stationary one at another distance. This is depicted in Figure 1 (p. 248). Thus, if subject motion and distance are specified, then object motion can be derived. Or, if subject motion and object motion are specified, then distance can be derived.

If distance information is supplied from a source independent of the optical flow, such as binocular convergence, the problem is easily solved. However, under monocular conditions, when only motion parallax itself is available to the subject as information about distance, the problem becomes more difficult. To be able to solve the equation under such conditions, the subject needs to be able to distinguish between optical change originating from object motion and optical change originating from subject motion. The subject needs to "know" if and how he or she moves and assume that all contingent optical motions are parts of the motion parallax. Then, position constancy can be obtained, object motion correctly identified, and information about absolute distance extracted. This fact opens a window to empirical studies. If one

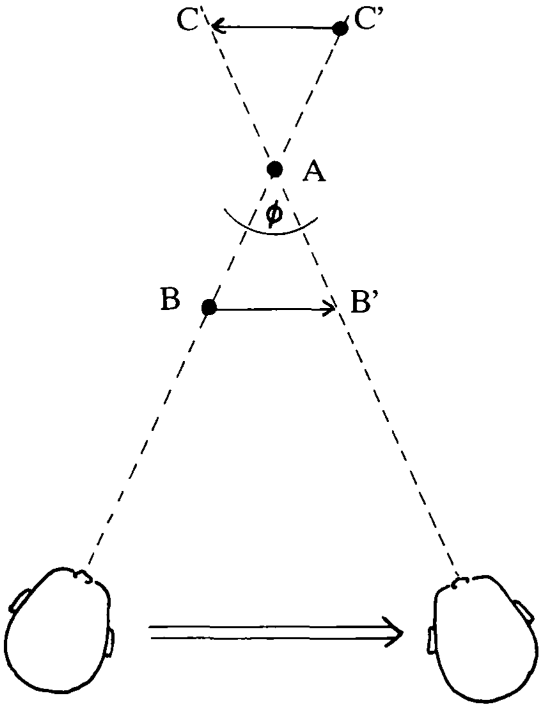

Figure 1. Ambiguity of object perception during observer motion. The same retinal displacement corresponds to either a stationary object at A, an object moving with the subject from B to B', or an object moving in the opposite direction to the subject from C to C'.

moves an object in the visual field contingent on the observer's motion, it should induce the perception of a stationary object that is perceived to be at a distance nearer of farther than its physical distance from the observer, if the observer uses motion parallax for distance perception.

In a recent study, Kellman, von Hofsten, Condry, and O'Halloran (1989) presented 16-week-old infants with contingently moving and stationary objects. A preferential-looking paradigm was used to determine whether the infants correctly identified the moving object. We assumed that if infants could detect one moving object in an array of stationary ones, they would tend to fixate that object preferentially. This assumption was based on many reported results indicating that infants show greater looking times to moving objects (e.g., see Volkmann & Dobson, 1976). We showed that the contingently moving object was preferentially fixated under binocular viewing conditions. However, no differential fixation was found under monocular viewing conditions. The results show that binocular perception in these subjects specified object distance accurately enough to enable the infant to perceive the moving object as moving. The absence of preferential looking for the contingently moving object in the monocular condition suggests that all objects were then seen as either stationary or all moving, and it is thus also possible that the perceived distance to the contingently moving object was altered.

One problem connected to the question of the emergence of motion parallax information about distance has to do with the relatively high velocity threshold found for young infants. Aslin and Shea (1990) and Dannemiller and Freedland (1989) both reported absolute thresholds for vertical motion in the 3-month-olds to be in the order of 4 to 5 deg/s. Somewhat lower values were reported by Volkmann and Dobson (1976), who found thresholds for horizontal oscillation to be on the order of 2 deg/s. The lowest velocity thresholds in the literature were reported by Kaufmann, Stucki, and Kaufmann-Hayoz (1985), who found that 3-month-old infants detected a rotary motion of 0.93 deg/s.

Only one study has reported differential velocity thresholds. Using linear motion of bars, Dannemiller and Freedland (1991) found that 20-week-old infants discriminated 3.3 deg/s but not 5.0 deg/s from 10.0 deg/s, and 2.0 deg/s but not 2.5 deg/s from 3.3 deg/s. If these values reflect true differential motion detection ability in motion parallax, a child moving the head sideways with a velocity of 4 cm/s would discriminate an object at a distance of 69 cm (3.3 deg/s) from one at 114 cm (2.0 deg/s) but not from one at 92 cm (2.5 deg/s). These differential motion thresholds are obviously too crude to be of much use in perceiving space. If motion parallax is to supply reasonably differentiated distance information to the infant, the perceptual system needs to be more sensitive to differential motion than indicated by Dannemiller and Freedland (1991).

Dannemiller and Freedland (1991) used preference of looking as their method of investigation. It is possible that the smallest velocity differences evoking preference of looking is higher than the smallest velocity differences perceived. A habituation paradigm might be a more sensitive instrument in detecting differential velocity sensitivity as it does not require looking preference, only detection of differences between habituation and test displays. Therefore, in the experiments to be reported, a habituation paradigm was used.

All infants were tested under binocular viewing, in spite of the possibility that the presence of binocular information might have confused the infants. The reasons for using binocular viewing were as follows. First of all, it is well known that every additional manipulation done on infant subjects increases the probability of fussing. Fussing during any part of the habituation or test procedures tends to obscure trends in the data, and fussing infants have to be excluded. Allowing natural, binocular viewing minimized this problem. Second, all infants were 15 weeks old, and we expected their binocular system to be rather crude (e.g., see Birch et al., 1982). Finally and most importantly, if the presence of binocular information had any effect on our subjects, the effect should work against our hypotheses. In all three experiments, the habituation display consisted of three rods aligned in the fronto-parallel plane. The middle rod moved contingent on the infant. Effects of binocular disparity on perceived depth would have counteracted any perceived depth induced by the contingent motion.

EXPERIMENT 1

The purpose of Experiment 1 was to get a first approximation of the sensitivity of young infants to motion parallax. The amplitude of differential motion chosen was a guess based on the assumption that habituation would be a more sensitive technique than preference of looking. Therefore we selected a value (0.32 deg/s) clearly below the earlier found threshold by Kaufmann et al. (1985). If the results indicated that infants did not detect this motion, we planned to increase amplitude in the next experiment, and if the results indicated that infants did detect this motion, we planned to decrease amplitude in the next experiment to get a better idea of the threshold value. Infants were habituated to a configuration of three rods aligned in the fronto-parallel plane. The middle rod moved contingently with the infant. After habituation, subjects saw two stationary displays in alternation. The first of these was spatially identical to the habituation display, that is, the three rods were aligned in the fronto-parallel plane. In the other test display, the middle rod was displaced backward 15 cm relative to the side rods, that is, to a position denoted by the motion parallax in the habituation display. The configuration of the rods was then triangular. If the infant had detected the contingent motion and perceived the middle rod to be at an altered distance, the triangular display should be perceived as familiar and the aligned display perceived as new. If the infant had not detected the contingent motion, the aligned display should be perceived as familiar and the triangular, as new.

Method

Subjects. Twenty-four subjects participated in Experiment 1. Twelve infants were habituated to the contingent motion display and were tested on the two stationary displays, and 12 infants received only the test trials. Their ages ranged from 101 to 113 days (M = 107 days). An additional 4 infants began the experiment but did not complete it because of fussing (3) and apparatus failure (1). In addition to these, 2 subjects were excluded because of slow habituation (more than 15 habituation trials). Dannemiller (1984) showed with Monte Carlo techniques that random variation in looking time starts to be an important factor in deciding when habituation criterion is reached when the number of habituation trials is large. Dannemiller suggested therefore that infants should be run for no more than 15 trials when using the 50% habituation criterion. This recommendation was followed in all the experiments of the present study.

Display and Apparatus. The infant was seated in an infant chair which moved sinusoidally back and forth in front of the display with a maximum velocity of 3.14 cm/s. The movement of the chair was produced by a motor. The front edge of the display box was 18 cm from the infant chair and about 39 cm from the eyes of the infant. Thus, the distance from the rods to the infant was approximately 85 cm. Black cardboard walls around the infant prevented him or her from seeing the experimenter.

The habituation display consisted of three vertical rods aligned in the fronto-parallel plane. The rods were all 20 cm high and 3 cm in diameter. They had a bright red coloring on which were attached small golden stars and small brightly colored squares. The distance between the two outer rods was 20 cm. The third rod was positioned in the middle of the display and moved contingently with the infant chair. The contingent motion was achieved by mechanical linkage between the infant's chair, the middle rod, and a pivot point 15 cm more distant than the moving rod. This meant that the optical change of the middle rod corresponded to a position in space of a stationary rod 15 cm more distant than the side rods. It also meant that the motion of the middle rod was always in phase with the motion of the subject (see Figure 1). The magnitude of the motion was 1.5 cm, and the maximum velocity was 0.47 cm/s, corresponding to a relative velocity of 0.32 deg/s compared to the outer rods.

There were two different test displays, both of which consisted of stationary rods. The first of these was spatially identical to the habituation display, that is, the three rods were aligned in the fronto-parallel plane. In the other test display, the middle rod was displaced backward 15 cm relative to the side rods, that is, to a position denoted by the motion parallax in the habituation display. The configuration of the rods was then triangular. If the infant detected the contingent motion and perceived the middle rod to be at an altered distance (contrary to its actual arrangement), the triangular display should be perceived as familiar and the aligned display perceived as new. If the infant did not detect the contingent motion (or its information was overridden by binocular information), the aligned display should be perceived as familiar and the triangular display, as new.

The infant viewed the three rods in a rectangular display case. The case's interior dimensions measured 82 cm across, 84 cm deep, and 64 cm high. The inside back wall of the display box was covered with horizontal stripes. The three rods were viewed against this background. Horizontal stripes were used so that accretion and deletion of background texture elements would not supply additional motion information. The distance from the front edge of the case to the three rods was 46 cm. A 5-cm high "hump" was placed at the front of the display box. The infant could see the rods but not their bases, the surface on which the display was standing, and not the mechanism which produced their movement. These additional features could otherwise have conveyed information about the position in depth of the middle rod relative

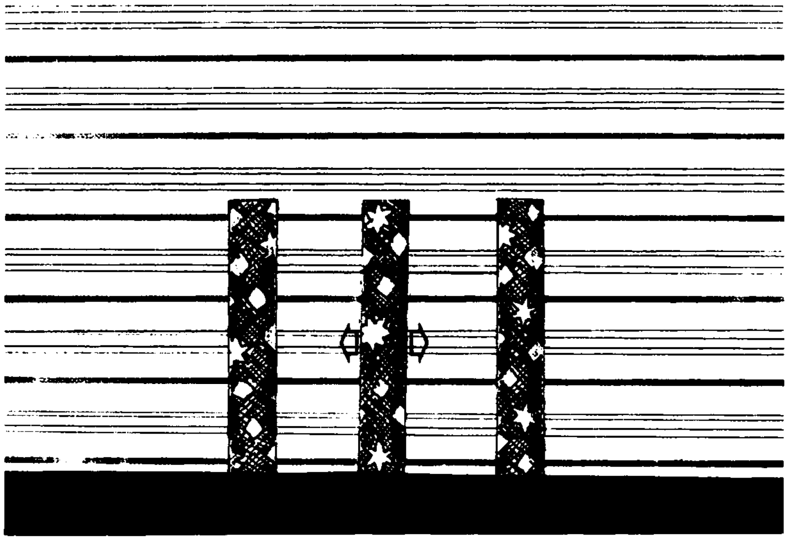

Figure 2. A sketch of the stimulus display of Experiment 1 from the infant's point of view (drawn from a photograph).

to the side rods. Illumination was provided by two 25-W spotlights placed in the upper front edge of the display case and kept from the subject's direct view by a wooden strip. Display presentation was controlled by a motor-driven curtain which opened and closed between the subject and the display box. There were two small peepholes in the back in the display box, one in the upper left corner and one in the upper right corner. The stimulus display is depicted in Figure 2 from the infant's point of view.

Procedure. An infant control habituation procedure was used to assess infants' perception of contingent motion. Each trial began with the opening of the curtain of the display box and the illumination of the display. After an initial 0.5-s fixation, a trial continued until a 2.0-s look away occurred, up to a maximum of 60 s of looking time. At the end of the trial, the curtain was closed. An intertrial interval of 5 s was used on all trials. This allowed enough time to change displays during the test trials. Opening and closing the curtains required another 3 s each. The contingent-motion display was shown on repeated trials until a criterion of habituation was met. The criterion was a 50% decline from a subject's initial looking time, calculated over three trial blocks. If total looking time on the first three trials did not exceed 12 s, the habituation criterion was set by the first three consecutive trials on which 12 s was exceeded.

Test trials consisted of alternating presentations of the aligned configuration and the triangular configuration of the three stationary rods. Test trials were in all other respects identical to habituation trials. The baseline group received only the test trials.

Fixation was recorded by two trained observers using a silent pushbutton input to an IBM PC computer. Light from the stimulus displays was adequate to allow accurate determination of fixation direction. The observers were blind to the order of the test displays. Percent agreement between the observers was calculated for each trial by sampling both observer buttons every hundredth of a second and calculating time of agreement as proportion of total time. Observer agreement averaged 84.5%.

To disguise the sound from the motors driving the infant chair and from the moving curtain, a tape-recorded soft female voice reading fairy tales was on during the whole experiment. Pilot testing showed that infants were less distracted and calmer with this procedure.

Results

Figure 3 shows the mean looking times for the 12 infants in the contingent-motion group and the 12 infants in the baseline group. It took infants, on the average, 8.8 trials to habituate to the contingent motion display. After habituation, infants responded more to the aligned test display than to the triangular test display, although the aligned test display was spatially more similar to the

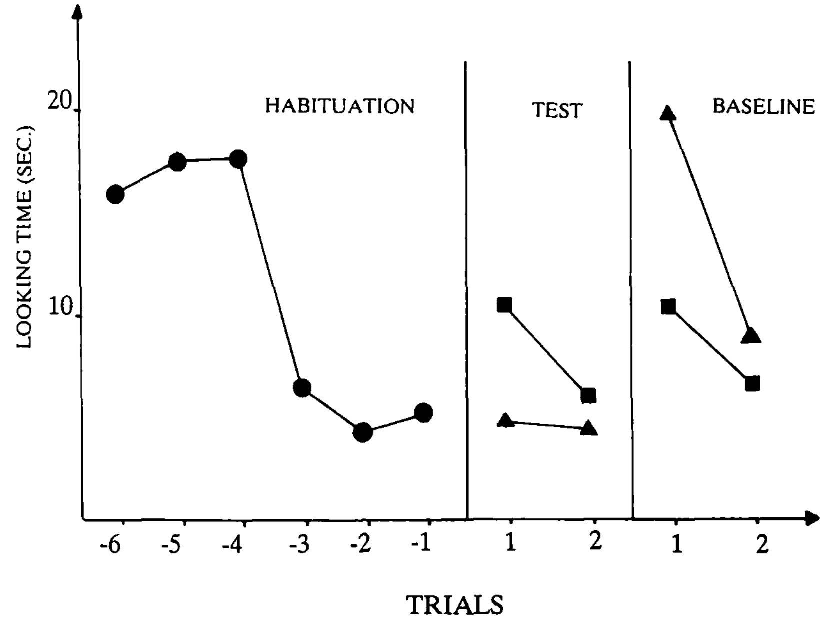

Figure 3. Mean looking times in Experiment 1. Circles denote habituation trials, squares denote trials with the aligned test display, and triangles denote trials with the triangular test display.

habituation display. The looking times on the first aligned-display test trial were reliably greater than the looking times in the last habituation trial, $t(11) = 3.75$, $p < .01$. However, the looking times on the first triangular-display test trial were not statistically different from the looking times on the last habituation trial, $t(11) = .34$, n.s.

Baseline-group infants, in contrast, started off looking more at the triangular test display. These patterns were confirmed by the analyses. A 2 (Group) × 2 (Test Display) × 2 (Test Trial) ANOVA on the test trial looking times showed a reliable trial by group interaction, $F(1, 22) = 8.02$, $p < .01$, and a reliable group by test display by trial interaction, $F(1, 22) = 9.63$, $p < .01$. The trial by group interaction reflects the fact that the decline in looking time over trials is different for the habituation group and the baseline group. The group by test display by trial interaction reflects the fact that there is a difference in looking preferences between the two test displays, but that it changes over the two test trials. Separate ANOVAs for each test trial showed that this interaction could be attributed to the first test trial, $F(1, 22) = 11.16$, $p < .01$. Subjects in the habituation group looked longer at the aligned test display, whereas infants in the baseline group looked longer at the triangular test display on their first test trial. Individual comparisons showed that 10 of the 12 subjects in the habituation group looked longer at the aligned test display ($p < .05$, sign test), whereas 8 of the 12 subjects in the baseline group looked longer at the triangular display (n.s., sign test).

Discussion

The results of the first experiment suggest that young infants are quite sensitive to contingent relative motion. The relative velocity used in this experiment was substantially slower than the thresholds calculated from earlier studies. In fact, the motion used, 0.32 deg/s, was only about a third of the slowest motion evoking preference looking in any of the earlier studies on motion thresholds in young infants. Kaufmann et al. (1985) found an absolute threshold for rotary motion in 3-month-olds of 0.93 deg/s.

The same rods were used in the habituation and both test displays. This step preserved the retinal size of the rods between the habituation display and the aligned test display. However, in the triangular test display, the retinal size of the middle rod was 17% smaller than in the habituation display. If infants had looked longer at the triangular display, this difference might have been the cause. However, in the present experiment, in spite of the introduced retinal difference between habituation and the triangular test display, infants looked longer at the aligned test display.

The fact that infants viewed the displays binocularly should also have favored more looking at the triangular display. Binocular vision should have equated the habituation display with the aligned test display. The change introduced into the triangular display by the constant size of the middle rod and the fact that the displays were viewed binocularly might have contributed to the spontaneous preference for the triangular display in the baseline group.

EXPERIMENT 2

The result of Experiment 1 indicated that the threshold for contingent motion is lower than 0.32 deg/s. The purpose of Experiment 2 was to test infants with a smaller retinal velocity to learn more about the motion sensitivity of young infants. The velocity of the infant chair was thus lowered to half its velocity in Experiment 1. The contingent motion of the middle rod in the three-rod display was consequently lowered to 0.16 deg/s.

Method

Subjects. Twelve subjects participated. All were habituated to the contingent motion display and tested on the two stationary displays. Their ages ranged from 104 to 111 days (*M* = 108 days). An additional 3 infants began the experiment but did not complete it because of fussing, and 1 infant was excluded because of slow habituation (more than 15 trials).

Display and Apparatus. These were the same as in Experiment 1, except that the infant chair moved sinusoidally back and forth in front of the display with a maximum velocity of 1.57 instead of 3.14 cm/s.

Procedure. The procedure was the same as in Experiment 1. Only a habituation group was run. It was compared to the baseline group of Experiment 1. Observer agreement averaged 85.6%.

Results

The distribution of looking time in the test trials was heavily skewed. This skewedness can partly be attributed to one single subject who increased looking from 7.2 s on the last habituation trial to over 60.0 s on the first test trial for the aligned display, corresponding to more than 30 *SD*s above the mean for the remaining 11 subjects on that test trial (*M* = 2.16 s, *SD* = 1.31 s). This subject was therefore considered as an outlier and was excluded from further data treatment. His total looking times on the test trials were 65.2 s and 78.5 s for the aligned and the triangular displays, respectively. The analysis is thus based on 11 subjects. Figure 4 (p. 256) shows the mean looking times for these 11 infants.

It took infants, on the average, 9.4 trials to habituate to the contingent motion display. After habituation, infants did not reliably increase looking to either of the test displays. The looking times on the last habituation trial were

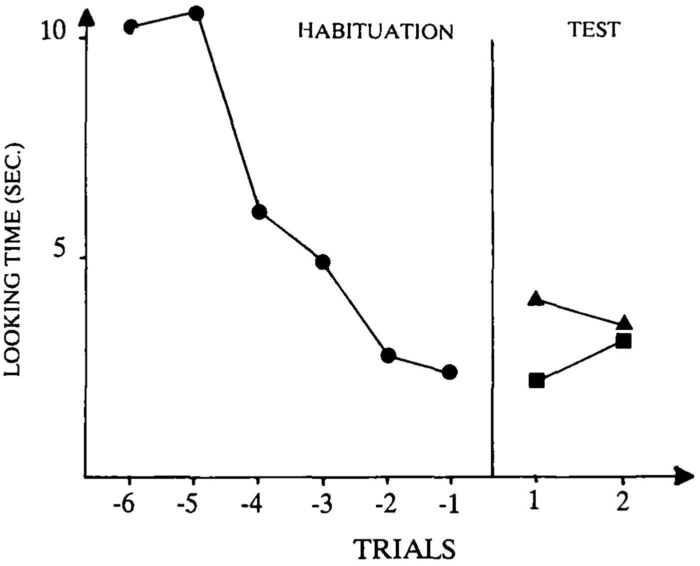

Figure 4. Mean looking times in Experiment 2. Circles denote habituation trials, squares denote trials with the aligned test display, and triangles denote trials with the triangular test display.

not statistically different from the looking times on the aligned test display, $t(11) = 0.94$, n.s., or the triangular-display test trial, $t(11) = 1.51$, n.s. Comparing the looking times on the two different test displays revealed that 4 of the 12 subjects (n.s., sign test) looked more at the aligned test display on the first test trial and 7 looked more at the aligned test display on the second test trial (n.s., sign test).

The results of Experiment 2 were compared to the control group of Experiment 1 who had seen the same test displays. A 2 (Group) × 2 (Test Display) × 2 (Trial) ANOVA on the test trial looking times showed a reliable main effect of group, $F(1, 21) = 6.16$, $p < .05$. The control group looked significantly more at the test displays. There was also a main effect of test display, $F(1, 21) = 4.68$, $p < .05$. The triangular display received more looking. However, there was no interaction between group and display, $F(1, 21) = 2.04$, or interaction between group, display, and trial, $F(1, 21) = 2.52$.

Despite the exclusion of one extreme subject, looking time distributions were still skewed. Therefore, the question was raised whether the failure of obtaining any interaction effects could have been a Type II error. To check for this possibility, a nonparametric test, the Wilcoxon Rank Sum *W* test, was performed on the differences in looking times between the two displays for each subject in the habituation and baseline groups. This test showed no differences for the two groups either at the first test trial, $W(11, 12) = 144$, n.s., or the second test trial, $W(11, 12) = 138$, n.s.

Discussion

The results of Experiment 2 indicate that the contingent motion of the middle rod was not detected by the infants. This would place the threshold for contingent motion somewhere between 0.16 and 0.32 deg/s.

EXPERIMENT 3

Although the results of Experiments 1 and 2 suggest that the sensitivity for contingent motion is remarkably high in the young infant, it does not prove that the contingent motion was used as information about distance. The habituation display and the triangular test display give rise to identical proximal motion patterns. Thus, if the infants were only concerned with optical displacement and not with motion in the world, they would still have perceived the aligned display as new. In fact, the results of Experiment 1 do not even tell us whether the infant detected the contingency between the object motion and the infant's motion. The purpose of Experiment 3 was to find out whether young infants are sensitive to the relation between small retinal motions and their own movements. The same habituation display was used as in the previous experiments, but the test displays were different. One of them had the same spatial configuration as the triangular display in the first experiment, that is, the middle rod was displaced backward as much as denoted by the motion parallax. In the other test display, the middle rod was displaced toward the subject in such a way that its retinal motion had the same magnitude as in the habituation display but in opposite phase. If infants just detected the motion of the middle rod, both test displays would look equally familiar. However, if they detected the relation between their own motion and the motion of the middle rod, they should find the test display with the rod displaced backward as familiar and the test display with the rod displaced forward as new.

Method

Subjects. Twenty-eight subjects participated in Experiment 3. Fourteen infants were habituated to the contingent-motion display and tested on the two stationary displays, and 14 infants received only the test trials. Their ages ranged from 102 to 114 days (M = 108 days). An additional 11 infants began the experiment but did not complete it because of fussiness (6) and equipment failure (3). In addition, 3 infants were excluded because of slow habituation (more than 15 trials).

Display and Apparatus. The apparatus was the same as in the previous experiments. The velocity of the infant chair was the same as in Experiment 1, that is, the chair moved sinusoidally back and forth in front of the display with a maximum velocity of 3.14 cm/s.

The habituation display consisted of three vertical rods aligned in the fronto-parallel plane. The rods were all 20.0 cm high and 2.5 cm in diameter. They were white with a pattern of random black spots. The side rods had two horizontal, bright green stripes near the top, and the middle rod had one green stripe at the top and five rows of alternating green and red squares. The distance between the two outer rods was 20 cm. The third rod was positioned in the middle of the display and moved contingently with the infant chair (in phase) 1.5 cm back and forth.

There were two different test displays. One of them had the same spatial configuration as the triangular display in the first experiment, that is, the middle rod was displaced away 15 cm (*away-display*). In the other test display, the middle rod was displaced toward the subject 11 cm (*toward-display*). This had the consequence that its retinal motion had the same magnitude as in the habituation display but in opposite phase (see Figure 5).

The size of the middle rod was adjusted in each of the two test displays so that it was retinally equal to the size of the middle rod in the habituation display. In the test display where the middle rod was displaced away from the subject 15 cm, it was thus scaled up 17%, and when it was displaced toward the subject, it was scaled down 13%. The pattern on each rod was also scaled up and down correspondingly. Equating the retinal size of the rods in the two

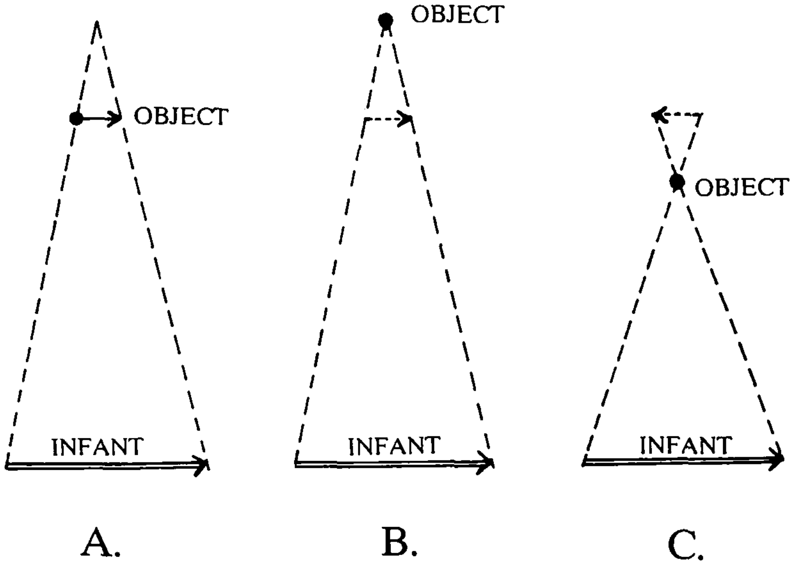

Figure 5. The displays used in Experiment 3. Display A is the habituation display. In this display, the object moves with the infant. Displays B and C are test displays. In Display B, the object is displaced away from the subject (away-display). The retinal motion from Display B is identical to the one from Display A. In Display C, the object is displaced toward the subject (toward-display). The retinal motion has the same velociiy as the one from Display A but in the opposite phase.

test displays with those in the habituation display was necessary to avoid explaining a preference for the display with the middle rod closer to the subject in terms of greater retinal size.

Procedure. This was the same as in the previous experiments with one important exception. In Experiments 1 and 2, the habituation criterion was set by the first three trials on which 12 s of looking time were exceeded. The following undesirable effect of that procedure was noticed. Sometimes the display caught the attention of the infant only after a few trials. In those cases, the 12-s criterion was often reached after two trials, or even one, with longer looking times. Thus, the criterion came to be made up of a mixture of long and short looking times, underestimating the initial interest and making it harder for the subject to complete the experiment. To avoid this problem, the criterion in Experiment 3 was defined by the three consecutive trials with the longest looking times above the 12-s threshold instead of the first three trials above. With this procedure, the criterion was shifted one trial ahead for 4 of the 14 subjects, and three trials ahead for 1. Observer agreement averaged 85.7%.

Results

Figure 6 (p. 260) shows the mean looking times for the 14 infants in the contingent-motion group and the 14 infants in the baseline group. It took infants, on the average, 7.6 trials to habituate to the contingent-motion display. After habituation (*M* looking on the last trial = 3.01 s), infants responded more to the test display with the middle rod displaced toward them (*M* looking time = 5.53 s) than to the test display with the middle rod displaced away from them (*M* looking time = 3.87 s). The looking times on the test trials with the toward-display were reliably greater than the looking times on the last habituation trial, $t(13) = 3.07$, $p < .01$. However, the looking times on the test trials with the away-display were not statistically different from the looking times on the last habituation trial, $t = 1.14$, n.s. On average, baseline-group infants looked slightly more at the toward-display (5.35 s) than at the away-display (4.58 s), but this difference was not statistically significant, $t = 0.49$. On the first trials, they actually looked more at the away-display (see Figure 6).

A 2 (Group) × 2 (Test Display) × 2 (Trial) ANOVA on the test trial looking times showed no interaction effects either between group and test display or between group, test display, and trial. However, the looking time distributions were quite skewed just as in Experiment 2. Therefore, the question was raised whether the failure of obtaining any interaction effects could have been a Type II error. To check for this possibility, a nonparametric test, the Wilcoxon Rank Sum *W* test, was performed on the differences in looking times between the two displays for each subject in the habituation and baseline groups. This test indicated that the looking patterns

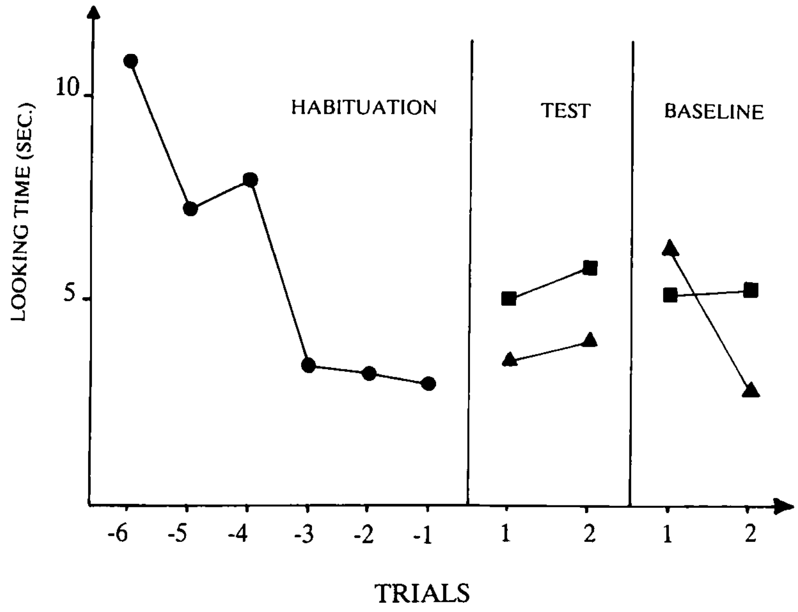

Figure 6. Mean looking times in Experiment 3. Circles denote habituation trials, triangles denote trials with Display B (see Figure 4), and squares denote trials with Display C.

for the two groups were different at the first test trial, $W = 244, p < .05$, one-tailed test, but not at the second test trial, $W = 202, p > .10$. Furthermore, individual comparisons showed that 10 of the 14 subjects in the habituation group looked longer at the toward-display ($p < .10$, sign test) on the first test trial, whereas only 5 of the 14 subjects in the baseline group did so (n.s., sign test).

Discussion

The results of the present experiment suggest that young infants are sensitive to the relation between their own motion and the relative retinal motions of visual elements. The infants who were habituated to a display in which the middle rod moved in phase with the subject increased their looking at a stationary test display in which the middle rod was displaced toward the subject in such a way as to preserve the same retinal velocity but reverse the phase relation between subject motion and the retinal motion of that rod. Looking time was not increased to a test display in which the middle rod was displaced away from the subject in such a way as to preserve both the retinal velocity and phase relation between subject motion and retinal motion of that rod.

The fact that the subjects viewed the displays binocularly might have tempered the results. Birch et al. (1982) found an earlier onset of crossed relative to uncrossed disparity in infants. Crossed disparities refer to points in space situated in front of the fixation point and uncrossed, to points in space situated behind. Birch et al. found that infants who had developed sensitivity to crossed but not uncrossed disparities looked longer at the crossed disparity than at the uncrossed in a visual preference test. It is possible that some of the infants were at that stage of development and increased their preference for the toward-display for that reason. However, this cannot explain why the toward-display received significantly more looking than the away-display in the experimental group but not in the baseline group. If subjects had tended to look longer at the toward-display because they were sensitive to crossed but not uncrossed disparities, the infants in the baseline group should also have demonstrated the same preference. Moreover, this difference between the experimental group and the control group had vanished by the second test trial, suggesting that it was an effect of the habituation exposure.

GENERAL DISCUSSION

The results of the present study suggest that young infants are much more sensitive to motion than previous studies have indicated. The relative motion detected in Experiment 1 was 0.32 deg/s, which is almost an order of magnitude slower than most earlier reports. The results of the three experiments rule out the possibility that the subjects detected and reacted to the displacements of the middle rod relative to the side rods (the fact that it is closer to one side rod at one time and closer to the other at a later time, etc.) rather than the motion itself. When velocity was decreased in Experiment 2, the subjects did not show any signs of detecting the difference between the motion display and the aligned test display. As the displacement of the middle rod was the same in both Experiments 1 and 2, it should also be equally detectable in both experiments. Only velocity differed. Furthermore, the displacement of both test displays in Experiment 3 was of equal amplitude. In spite of that, the subjects tended to treat as new the test display in which the relative motion of the middle rod was in opposite phase.

There are at least two possible reasons for the discrepancy between the results of the present study and earlier ones (Aslin & Shea, 1990; Dannemiller & Freedland, 1989, 1991; Kaufmann et al., 1985). First, the habituation paradigm might be a more sensitive instrument than preference looking in evaluating the sensitivity to motion in infants. Preferential looking is not a necessary consequence of detecting motion. Infants might detect very slow motions but not be attracted by them. The second possibility is that the threshold for detecting slow contingent motions is lower than the threshold for detecting other kinds of motion, and that the perceptions of these different kinds of motion are quite different. In other words, the detection of slow contingent motions might be functionally specific, and perceived motion might not be evoked at all but rather perception of structural depth. Rogers and Graham (1979) reported that their subjects did not perceive any relative motion within the displays but only depth. Is it possible that the sensitivity to motion parallax information is another hyperacuity? The threshold value suggested by this study and the sensitivity of adults to this optical information found by Rogers and Graham speaks in favor of that. Steroacuity becomes superior to grating acuity after the third month and remains so for the rest of life (Gwiazda, Bauer, & Held, 1989). Like contingent relative motion, disparity is not perceived as such but in terms of depth.

Although the present study suggests that 3½-month-old infants detect both slow retinal motions and the contingency between these motions and their own movements, it does not prove that contingent motions are perceived in terms of distance rather than in terms of motion per se. To show that, we need to disentangle proximal and distal variables. This is most easily done by using different distances from the subject to the habituation display and to the test displays. Then all proximal differential velocities are changed, but the spatial relations remain the same. Such an experiment should be done.

There is evidence that neonates might have some ability to perceive object size and distance (Granrud, in press), but it is yet unknown how this is done. Is it conceivable that motion parallax could provide the infant with the means to perceive egocentric distances in space at this early age? It should be pointed out that this is a more sophisticated perceptual ability than the one tested for in the present study. The perception of egocentric distance from motion parallax not only requires a sensitivity to contingent differential motion but also "knowledge" of one's own movement. Recently, however, Jouen and Lepecq (1989) found evidence of sensitivity to optic flow information for regulating posture in 3-day-old infants. Thus, it is logically possible that ego-motion could be extracted from optical changes at that age and used in perceiving egocentric distance via motion parallax. However, if that is so, such a system needs to be calibrated in some way before it can be used even in a crude way and that may speak against motion parallax being used by Granrud's subjects. Evidence against motion parallax being used by Granrud's subjects is also the fact that the objects moved in his study, which should tend to obscure motion parallax information.

REFERENCES

Aslin, R., & Shea, S. (1990). Velocity thresholds in human infants: Implications for the perception of motion. *Developmental Psychology*, *26*, 589–598.

Birch, E.E., Gwiazda, J., & Held, R. (1982). Stereoacuity development for crossed and uncrossed disparities in human infants. *Vision Research*, *22*, 507–513.

Carroll, J.H., & Gibson, E. (1981, April). *Differentiation of an aperture from an obstacle under conditions of motion by three-month-old infants.* Paper presented at the meeting of the Society for Research in Child Development, Boston, MA.

Dannemiller, J.L. (1984). Infant habituation criteria: 1. A Monte Carlo study of the 50% decrement criterion. *Infant Behavior and Development*, *7*, 147–166.

Dannemiller, J.L., & Freedland, R.L. (1989). The detection of slow stimulus movement in 2- to 5-month-olds. *Journal of Experimental Child Psychology*, *47*, 337–355.

Dannemiller, J.L., & Freedland, R.L. (1991). Speed discrimination in 20-week-old infants. *Infant Behavior and Development*, *14*, 163–173.

Eriksson, E.S. (1972). *Movement parallax and distance perception* (Report No. 117). Uppsala, Sweden: University of Uppsala, Department of Psychology.

Fox, R., Aslin, R.N., Shea, S.L., & Dumais, S.T. (1980). Stereopsis in human infants. *Science*, *207*, 323–324.

Gibson, E.J., & Walker, A. (1984). Development of knowledge of visual-tactual affordances of substance. *Child Development*, *55*, 453–460.

Gibson, J.J. (1950). The perception of visual surfaces. *American Journal of Psychology*, *63*, 367–384.

Gibson, J.J., Gibson, E.J., Smith, O.W., & Flock, H. (1958). Motion parallax as a determinant of perceived depth. *Journal of Experimental Psychology*, *58*, 40–51.

Granrud, C.E. (in press). Visual size constancy in newborn infants. In C.E. Granrud (Ed.), *Visual perception and cognition in infancy*. Hillsdale, NJ: Erlbaum.

Granrud, C.E., Yonas, A., Smith, I.M., Arterberry, M.E., Glicksman, M.L., & Sorknes, A.C. (1984). Infants' sensitivity to accretion and deletion of texture as information for depth at an edge. *Child Development*, *55*, 1630–1636.

Gwiazda, J., Bauer, J., & Held, R. (1989). From acuity to hyperacuity: A 10-year update. *Canadian Journal of Psychology*, *43*, 109–120.

Held, R., Birch, E.E., & Gwiazda, J. (1980). Stereoacuity of human infants. *Proceedings of the National Academy of Science U.S.A.*, *77*, 5572–5574.

Helmholtz, H. von (1925). *Physiological optics* (Vol 3). Rochester, NY: Optical Society of America.

Johansson, G. (1973). Monocular motion parallax and near-space perception. *Perception*, *2*, 135–146.

Johansson, G., von Hofsten, C., & Jansson, G. (1980). Event perception. *Annual Review of Psychology*, *31*, 27–63.

Jouen, F., & Lepecq, J.-C. (1989). La sensibilité au flux optique chez le noveau-né [Sensitivity to optical flow in the neonate]. *Psychologie Francais*, *34*, 13–18.

Kaufmann, F., Stucki, M., & Kaufmann-Hayoz, R. (1985). Development of infants' sensitivity for slow and rapid motions. *Infant Behavior and Development*, *8*, 89–98.

Kellman, P.J. (1984). Perception of three-dimensional form by human infants. *Perception & Psychophysics*, *36*, 353–358.

Kellman, P.J., von Hofsten, C., Condry, K., & O'Halloran, R. (1989, July). *Motion and stability in the world of the (moving) infant*. Paper presented at the Conference on Event Perception and Action, Miami, OH.

Kellman, P.J., von Hofsten, C., & Soares, J. (1987). Concurrent motion in infant event perception. *Infant Behavior and Development*, *10*, 1–10.

Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception*, *8*, 125–134.

Volkmann, F.C., & Dobson, M.V. (1976). Infants' responses of ocular fixation to moving visual stimuli. *Journal of Experimental Child Psychology*, *22*, 86–99.

Yonas, A., Arterberry, M.E., & Granrud, C.E. (1987). Four-month-old infants' sensitivity to binocular and kinetic information for three-dimensional-object shape. *Child Development*, *58*, 910–917.

Yonas, A., & Granrud, C.E. (1985). Development of visual space perception in young infants. In J. Mehler & R. Fox (Eds.), *Neonate cognition: Beyond the blooming, buzzing confusion*. Hillsdale, NJ: Erlbaum.

Yonas, A., Petterson, L., & Lockman, J.J. (1979). Young infants' sensitivity to optical information for collision. *Canadian Journal of Psychology*, *33*, 268–276.

Yonas, A., Petterson, L., Lockman, J.J., & Eisenberg, P. (1980, April). *The perception of impending collision in 3-month-old infants*. Paper presented at the International Conference on Infant Studies, New Haven, CT.

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