

Infants' Perception of Kinetic Depth and Stereokinetic Displays

Mark A. Schmuckler and Dennis R. Proffitt

Studies examined infants' perceptions of 3-dimensional form, using a kinetic depth effect (KDE) display and displays containing subsets of the motion present in the KDE display. One subset consisted of "between-contour" motion, and the second consisted of "within-contour" motion. Research with adults has suggested that only between-contour motion leads to a compelling depth percept. In Experiments 1 and 2, infants generalized habituation from a KDE display to the between-contour but not the within-contour changes. In Experiments 3 and 4, infants generalized habituation from a KDE display to the between-contour display viewed from a novel orientation but not to the within-contour display viewed from the original orientation. Results indicate sensitivity to between-contour but not within-contour information, suggesting that infants perceive the 3-dimensional form of these displays.

Two compelling demonstrations of people's ability to extract depth from motion are the kinetic depth effect (KDE), described by Wallach and O'Connell (1953), and the stereokinetic effect (SKE), reported by Musatti (1924). Described simply, a KDE display is a two-dimensional projection of a three-dimensional form revolving about an axis other than the line of sight. Wallach and O'Connell produced such displays by placing objects (either solid forms or wire figures) between a light source and a translucent screen and rotating these objects. This arrangement resulted in a transforming shadow on the screen that was perceived as the projection of a three-dimensional form when moving but not when stationary (Wallach & O'Connell, 1953). Similarly, the SKE consists of a moving two-dimensional display that induces a percept of three-dimensional form. The middle panel of Figure 1 illustrates the most common version of an SKE display, which consists of a set of nested circles with a constant eccentricity.¹ When rotated on a vertical turntable, this display produces a compelling percept of a three-dimensional form (either a cone pointing outward or a funnel receding inward). Interestingly, this percept is essentially an illusion; that is, there is no rigid, three-dimensional object that could generate this pattern of two-dimensional changes.

Investigations of the stereokinetic effect have shown that changes in different stimulus aspects of the display influence perceptions of depth. For example, Robinson, Piggins, and Wilson (1985) found that the perceived height of an SKE cone was independent of the number of contours or bands appearing on the SKE display but that the perceived height was strongly dependent on the eccentricity (i.e., displacement of the circles relative to one another) in the display, with apparent height increasing with eccentricity. Wilson, Robinson, and Piggins (1986) found that the perceived height of the cone decreased as the displays became more elliptical. Similar phenomenological approaches can be seen in studies by Bressen and Valloritagara (1986a, 1986b, 1987) and Mefferd (1968a, 1968b, 1968c; Wieland & Mefferd, 1968).

Recently, Proffitt, Rock, Hecht, and Schubert (1992) provided an analysis of the stimulus bases for the KDE and SKE. In essence, they showed that when a rigid cone is rotated in the same manner as the one seen in the SKE display, its motions can be decomposed into two components, one present in SKE displays and the other absent. The motions seen in an SKE cone display are similar to those experienced by a person who closes one eye and points an index finger at the other eye, inclines the finger so that it points toward the top of the head, and moves just the tip of the finger so that it draws a circle in the virtual picture plane having a constant radius around the line of sight. The tip of the cone is seen as inclined away from the line of sight, and it moves around the line of sight in a circle. Also, as with the finger example, the cone itself does not appear to rotate around its major axis. The contours on the cone maintain their orientation as the major axis of the cone swings around the line of sight.

The middle panel of Figure 1 presents a schematic diagram of three contours on a cone that rotates in a manner consistent with an SKE cone. The cone is shown at four locations of its rotation, separated in phase by 90°. In terms of the finger example, the motions depicted are those that would occur if

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¹ Each circle is positioned off-center relative to its immediately surrounding circle in the same direction and by an amount that is a constant proportion of the surrounding circle's radius.

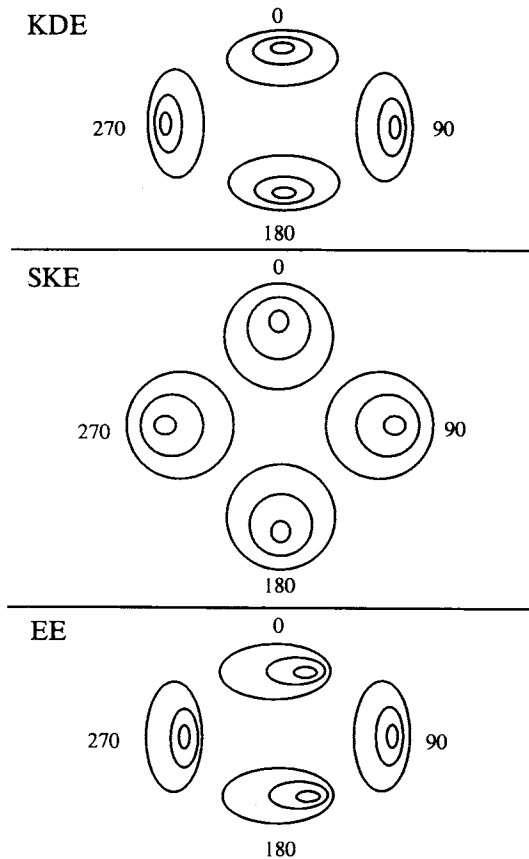


Figure 1. Schematic drawings of the kinetic depth effect (KDE), stereokinetic effect (SKE), and elastic effect (EE) displays used in Experiments 1 and 2.

the shallow cone were a thimble on the tip of the finger used to draw a circle around the line of sight. At 0° the cone points above the person's head, at 90° it points toward the right ear, and so forth. Again, it is important to note that the cone is not rotating around its own axis; that is, if one of the contours on the cone had been marked to resemble a clock face, then 12:00 would be the uppermost point on the contour, regardless of its rotational phase. The major axis of the cone continuously changes its orientation relative to the picture plane; however, the cone itself does not revolve around its own axis.

The motions inherent in the KDE display depicted in the top panel of Figure 1 can be decomposed into two distinct components. The first was called *between-contour motions* by Proffitt et al. (1992). Notice that the contours in the top panel are never concentric; instead, at 0° their projections are displayed off-center in an upward direction, at 90° they are displaced to the right, and so forth. Thus, each contour moves around the stations of the clock relative to the contours within which it is embedded. These between-contour motions are shared by the SKE cone display, with the contours in the SKE display moving relative to each other in exactly the same manner as they do for the rigid cone depicted in the KDE display. The between-contour motions in the SKE cone display are completely consistent with those occurring in the

projection of a rigid cone moving in a similar manner. The SKE illusion of depth will not be evoked by any arbitrary set of relative motions between contours. Between-contour motions must be consistent with those of a rigid-object motion if they are to evoke a perception of a rigid object moving in depth. As was elaborated by Proffitt et al., the motions that support the SKE illusion are not limited to those discussed here for the SKE cone.

If the between-contour motions are subtracted from the KDE display shown in Figure 1, then a second motion component remains, which Proffitt et al. (1992) called *within-contour motions*. Notice in the KDE display that the circular contours on the cone project as ellipses onto the picture plane because of their inclination relative to this plane. As the cone revolves, the orientation of its major axis changes direction relative to the projection plane, although the absolute value of its inclination remains the same. Thus, at 0° the contours have been rotated relative to the projection plane's horizontal axis, resulting in a foreshortening of their vertical dimension. At 90° the contours have been rotated around the picture plane's vertical axis, resulting in a foreshortening of the horizontal dimension. The bottom panel of Figure 1 shows the within-contour motions in isolation for the KDE display depicted in the figure. The 90° between-contour position was arbitrarily selected, and the contours are shown foreshortened in different directions as is consistent with their changing orientation relative to the projection plane. Because the contours themselves are not revolving around the major axis of the cone, the projected distances between particular locations on an individual contour are continuously changing.

With these distinctions it is easy to see the relationship between the KDE and SKE displays. A KDE display contains both between-contour and within-contour motion information. An SKE display contains the same between-contour information that specifies changes in the orientation of the object. Proffitt et al. (1992) pointed out that the motions present in the SKE display are consistent with the information occurring in small rotations of a three-dimensional, rigid object. This is because within-contour motions are not perceptually salient until the contours' observer-relative slant is greater than about 15° . As such, it is the presence of between-contour information that underlies observers' perceptions of depth both in KDE displays having small within-contour motions and in SKE displays.

Proffitt et al. (1992) examined the relative importance of these component transformations in an extensive series of experiments. In their initial study, viewers saw computer-generated, rotating cones containing both between- and within-contour motion (a KDE display), between-contour information only (an SKE display), and within-contour motion only (what Proffitt et al. called the *elastic effect*, or an EE display, as is presented in the bottom panel of Figure 1). Spontaneous reports indicated that both the KDE and SKE displays produced an impression of three-dimensional form; in contrast, EE displays evoked few such descriptions. Similarly, ratings of the amount of depth, the compellingness of depth, and the rigidity of the object indicated that the EE display was seen as having less depth than KDE and SKE

displays, was less compelling in its evocation of depth, and was not rigid. Subsequent studies extended the generality of these findings to novel figures (nested polygons and surfaces), displays involving translatory (as opposed to rotary) motion, texture gradients, and so on. Overall, these studies led to a common conclusion: For adults, between-contour motions alone evoke compelling percepts of three-dimensional objects, whereas within-contour motion in isolation fails to produce a percept of three-dimensional form.

The Ontogeny of Depth From Motion

In recent years there has been a growing interest in the development of sensitivity to depth information conveyed through motion. Some studies have examined the development of response to kinetic information specifying depth. This research has looked at the sensitivity to looming, or optical expansion patterns (Petersen, Yonas, & Fisch, 1980; Yonas, 1981; Yonas, Petersen, & Lockman, 1979), the perception of accretion and deletion of texture that specifies depth information (Granrud et al., 1984), and so on. Other work has focused more specifically on the development of infants' ability to perceive three-dimensional form, using both static and moving displays. For example, Bower (1966) reported evidence that 8-week-old infants responded similarly to a rectangular form despite differences in the figure's slant; this suggests an appreciation of three-dimensional form by way of shape constancy. This result has been refined and extended by other researchers (Caron, Caron, & Carlson, 1978, 1979; Cook, Field, & Griffiths, 1978; Day & McKenzie, 1973). Despite some apparent contradictions, these studies demonstrate that infants as young as 12 weeks are sensitive to invariant two-dimensional shape despite differences in slant.

Other research has investigated more directly infants' perception of depth and three-dimensional form, using motion stimuli. Owsley (1983), testing 4-month-old infants, found evidence that they discriminated solid, three-dimensional shapes on the basis of motion information. Infants were habituated to a continuously rotating wedge, a stationary wedge viewed from a single angle, or a series of static views of a wedge. After habituation, infants who had seen the continuously rotating wedge dishabituated more to a new form than infants who had seen either the stationary wedge or the discrete series of views of the wedge. These results imply that 4-month-old infants use kinetic information when perceiving the three-dimensional form of objects.

Probably the best evidence for infants' perception of three-dimensional form from kinetic information has been provided by Kellman (1984; Kellman & Short, 1987). Kellman presented 4-month-old infants with videotaped projections of a three-dimensional object continuously rotating (a kinetic depth stimulus), with two different axes of rotation shown during habituation. For comparison, two other groups of infants viewed a series of static slides of the object, circumscribing the same rotation as the continuously rotating stimuli. After habituation, infants saw either the same object rotating around a novel axis of orientation or a different object rotating around the new axis. Infants who had seen the

continuously rotating object generalized habituation to the same object in a new rotation and dishabituated to a different object in the new rotation. In contrast, infants who had seen the static sequences failed to dishabituate to either condition. Later work by Kellman and Short (1987) replicated and extended these findings. Using essentially the same paradigm, Kellman and Short also found that infants perceived the three-dimensional form of an object only after viewing continuous, transforming optical projections. In this case, however, the continuously changing projections were produced by moving the infant relative to a stationary object, as opposed to moving the object relative to a stationary infant.

Generally, then, there is compelling evidence that infants make use of depth-from-motion information. Specifically, continually transforming projective information, such as that which occurs in a KDE display, produces a compelling three-dimensional percept. However, no work has yet determined what makes up the essential aspect(s) of this motion information. What are the sources of information available in these projective displays, and are infants sensitive to this information in isolation? The experiments reported in this article address these concerns, using KDE displays.

Experiment 1: Discrimination of KDE, SKE, and EE Displays

This initial study examined infants' sensitivity to various types of motion information available in continuously transforming two-dimensional displays, specifically, the between- and within-contour motion information available in KDE, SKE, and EE displays. As described earlier, the between-contour information that occurs in both KDE and SKE patterns underlies adults' perceptions of three-dimensional form; within-contour motions seem to be relatively unimportant in inducing depth from motion. The current study provides evidence that infants similarly respond differentially to between- and within-contour information.

Method

Subjects. The final sample consisted of twelve 5-month-old infants (mean age = 21.9 weeks). An additional 4 babies were tested but not included in the final sample because of fussiness, equipment failure, and so on. Babies were recruited from birth announcements in the local newspaper and were drawn from the Charlottesville, Virginia community.

Stimuli. Three stimulus display patterns (KDE, SKE, and EE) were produced (shown schematically in Figure 1). All displays consisted of a series of six rotating nested ovals. The ratio of major to minor axes of the ovals of the KDE and EE displays was approximately 1.25:1. All stimuli were initially generated with a Sun 3/60 workstation having a high-resolution graphics monitor (33.5 cm wide and 25 cm high, 1,152 × 900 pixels) and then recorded onto videotape for later presentation to the infants. All stimuli appeared as light gray oval contours presented on a dark gray background.

Design. An infant-control habituation-of-looking time procedure (e.g., Horowitz, Paden, Bhana, & Self, 1972) was used to test discrimination of these displays. In this procedure, a stimulus (called the *habituation* stimulus) is presented repeatedly until visual attention to this stimulus drops (i.e., until the infant becomes bored).

In this study, boredom was defined as the total looking time on three consecutive trials that did not amount to more than half of the total looking time on the first three trials. When infants reach this criterion level, they are shown the "test" or "dishabituation" stimuli. The amount of looking time at these test stimuli is the main dependent measure and generally indexes the similarity perceived by the infants between the habituation stimulus and the dishabituation stimuli. If the infant considers the habituation and test stimuli comparable on some basis, then little renewed interest is observed; if the displays are perceived as different, then the infant becomes interested in the patterns once again.

In this experiment, the habituation stimulus consisted of the KDE display described above, and the test stimuli were the SKE and EE patterns. The two test stimuli were alternated for two trials each. Half the infants saw the test patterns in the order SKE—EE—SKE—EE, while the remaining infants saw the test displays in the order EE—SKE—EE—SKE.

Apparatus and procedure. Infants were tested in a small room containing a wooden chamber that was used to present the stimuli while permitting observation of their visual behavior. Each infant sat on his or her parent's lap and faced a half-silvered mirror positioned at a 45° angle from the line of sight. A Dage 650SN videocamera was located behind the mirror, and a Panasonic TR-195MB videomonitor was located off to the side. This apparatus makes possible the simultaneous presentation of video images and videotape recording of an infant's visual fixation. Ambient light level within the room during testing was kept low. All on-line computations, along with presentation of the stimuli, were controlled by an Apple II computer located in the adjacent control room; control of this computer is described in Kramer, Bertenthal, and Bai (1986).

Testing began when the infant seemed awake and alert. Parents were asked not to interact with their children and not to look at the displays during the experiment. An observer viewed the infant's visual behavior on a Panasonic WV-5400 videomonitor in the adjacent control room, and coded the beginnings and endings of fixations by toggling the space bar on the computer. A trial began when the infant first fixated the display, and ended when the infant had looked away from the display for 2 s. After each trial, the computer rewound the stimulus tape and began displaying the stimulus again. After the criterion was reached, the computer automatically showed the test displays in the order defined by the selected condition. The entire session was videotaped for later reliability coding.

Reliability. The observer in the control room scored all visual fixations during the experiment. A second observer subsequently performed reliability measures on the infants' visual fixations from the videotape recordings. This observer was unaware of the order condition for the infants. The mean absolute difference in looking time between these two observers was 0.59 s, with a range from 0.14 to 1.26 s.

Results and Discussion

The principal goal of the data analysis was to determine whether infants discriminated among KDE, SKE, and EE displays. Discrimination was assessed by comparing the looking time (in seconds) to the final two habituation trials (KDE), the two SKE test trials, and the two EE test trials; a significant increase in looking time to the SKE or EE trials, relative to the KDE trials, indicates discrimination. Looking times were compared using a two-way analysis of variance (ANOVA), with the within-subject variable of trial type (KDE, SKE, and EE) and the between-subject variable of test order (SKE/EE vs. EE/SKE). Figure 2 shows the mean total

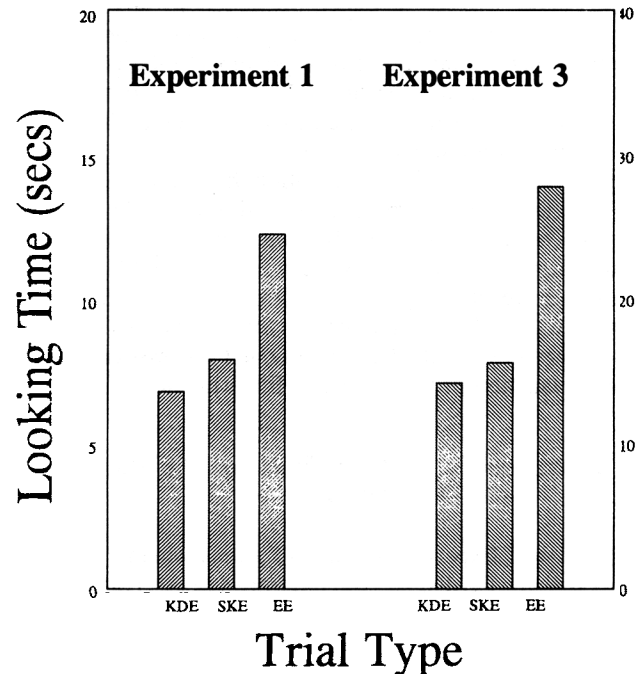


Figure 2. Mean total looking times (in seconds) to the final two kinetic depth effect (KDE; habituation) displays, the stereokinetic effect (SKE; dishabituation) displays, and the elastic effect (EE; dishabituation) displays used in Experiments 1 and 3. Standard errors of the looking times to KDE, SKE, and EE displays were 0.96, 1.21, and 2.02 s, respectively, in Experiment 1; and 3.14, 1.80, and 4.25 s, respectively, in Experiment 3.

looking times to the different habituation and test trials, averaged across test order. This analysis revealed a significant effect of trial type, $F(2, 20) = 6.31, p < .01$, but no effect for test order, $F(1, 10) = 0.16, ns$, and no interaction between the two variables, $F(2, 20) = 0.47, ns$.

Subsequent analyses compared the means for these trials, using Tukey's HSD test (see Kirk, 1982). Comparison of all pairwise means revealed that the amount of time spent looking at the final two KDE trials and the SKE test patterns did not differ significantly (mean difference = 1.23, *ns*). There was a significant difference between the looking times to the final KDE trials and the EE trials (mean difference = 5.56, $p < .01$), and a significant difference between the looking times at the EE and SKE trials (mean difference = 4.34, $p < .05$).

Infants did not dishabituate to the SKE display following habituation to the KDE display, which suggests that they perceived the KDE display as similar to the SKE display. In contrast, the EE pattern was seen as different from these two patterns; infants exhibited significant recovery of looking time toward the EE display, relative to both the habituation display (KDE) and the other test display (SKE).

What is the likely basis for this differential discrimination? To adults, both KDE and SKE stimulus displays appear as three-dimensional cones rotating in space; in contrast, the EE display induces little depth. These phenomenological impressions are supported both by informal observations in our

laboratory, as well as the experimental results of Proffitt et al. (1992). Correspondingly, one explanation of the current results is that infants are also responding to the perceived depth relations of the current displays. Both KDE and SKE patterns are seen as three-dimensional, while the EE pattern appears two-dimensional.

Before accepting this interpretation, however, it is necessary to rule out the more obvious (and uninteresting) alternatives. One possibility involves the nature of the experimental methodology. Infants' recovery to the EE display could be the result of a general preference for the EE display relative to the SKE; it might be that the EE pattern is simply more interesting to infants. Experiment 2 addresses this possible explanation of the results of Experiment 1.

Experiment 2: Looking Times to SKE and EE Displays

The goal of Experiment 2 was to assess whether infants' recovery to the EE display resulted from a general preference for that pattern, relative to the SKE display. If the EE display is inherently more compelling than the SKE display, we would expect that infants would spend more time looking at the EE display when it is presented without a prior habituation phase than they would looking at the SKE pattern. However, if nothing in the EE display is inherently more interesting, then looking times should be approximately equivalent.

Method

The participants were twelve 5-month-old infants (mean age = 21.8 weeks). An additional 5 babies were tested but were not used due to fussiness (2) or equipment malfunction (3). Babies originally were identified through birth announcements and other public records. All babies were recruited from the Scarborough, Ontario, community.

The stimulus displays used in this experiment consisted of the SKE and EE displays described in Experiment 1. All infants received three trials with the SKE display and three trials with the EE display; these trials were alternated. Half of the infants saw the displays in the order SKE—EE—SKE—EE—SKE—EE, and the remaining infants saw them in the reverse order.

Each infant was tested in a small room covered with acoustic panelling. The infant sat on his or her parent's lap facing a Sony CVM-194 videomonitor, which was set approximately 3 in (7.6 cm) above a table surface. A JVC GS-CD1U videocamera was positioned under the videomonitor, making it possible to focus on and videotape the infant's face. Stimulus presentations and on-line computations of looking time were controlled by an IBM-compatible PC located in the adjacent control room.

Testing began when the infant was awake and alert. The parent was asked to not interact with the child, and to avoid looking at the displays during the experiment. An observer, viewing the infant's visual behavior on a Sony CVM-950 videomonitor in the adjacent control room, coded the beginnings and endings of fixations by toggling the space bar on the computer. A trial began when the infant first fixated on the display, and ended when the infant looked away from the display for 2 s. After each trial the computer either forwarded or rewound the videotape to move to the next trial. The entire session was videotaped for later reliability coding.

The observer in the control room scored all visual fixations during the experiment. A second observer subsequently performed reliability measures on the infants' visual fixations from the videotape recordings. This observer was unaware of the order condition for the infants. The mean absolute difference between these two sets of looking times was 0.70 s, with a range from 0.33 s to 1.84 s.

Results and Discussion

The principal goal of the data analysis was to determine whether infants looked preferentially to either the SKE or EE displays. Comparisons were made using a three-way ANOVA, with the within-subject variables of trial type (SKE or EE) and repetition (first, second, or third presentation), and the between-subject variable of order (SKE/EE vs. EE/SKE). This analysis failed to reveal any significant main effects or interactions. Most important, the mean total looking time to the SKE display (8.82 s) did not differ from the mean looking time to the EE display (7.95 s), $F(1, 10) = 0.25, ns$.

The interpretation of this result is straightforward: Infants found the SKE and EE displays equally interesting. This finding supports the idea that infants' greater looking time to the EE display (relative to the SKE display) observed in Experiment 1 occurred because of a perceived similarity between the KDE and SKE displays, and a corresponding dissimilarity between KDE and EE displays, and not because of an inherent preference for the EE displays.

Is perceived depth the underlying basis for the perceived similarity between KDE and SKE displays? On the basis of Proffitt et al.'s (1992) results, both SKE and KDE evoke perceptions among adults of similar three-dimensional objects. Similarly, infants appear to perceive similarity based on between-contour motions. As such, it is tempting to suppose that infants perceive the depth relationships inherent in these displays. However, it is still conceivable that infants discriminated on the basis of some other two-dimensional, proximal characteristic of these projections, without any recognition of its three-dimensional structure. Experiments 3 and 4 extend these results, examining KDE and SKE displays that are more widely divergent in terms of their two-dimensional stimulus bases, but which have strong similarity in terms of their three-dimensional form.

Experiment 3: Discrimination of KDE, SKE, and EE Displays in Novel Orientations

Proffitt et al. (1992) noted that although the KDE and SKE displays evoked similarly compelling depth ratings, the perceived height of the KDE display used in our experiments was significantly less than the apparent height of the SKE display. To assess the importance of apparent height differences in these displays, Proffitt et al.'s third experiment used displays in which the perceived height of these patterns was made equivalent. The investigators varied the apparent height in KDE displays by increasing the eccentricity of the display, extending the tip of the cone out beyond its base; a schematic representation of this display is shown in the top panel of Figure 3. For comparison purposes, an EE display

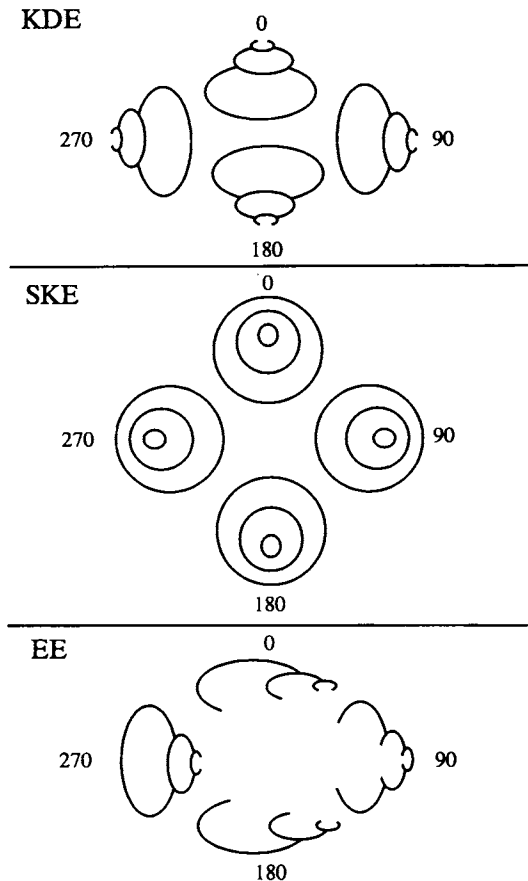


Figure 3. Schematic drawings of the kinetic depth effect (KDE), stereokinetic effect (SKE), and elastic effect (EE) displays used in Experiments 3 and 4.

was constructed with a similar eccentricity to that of the KDE display; this pattern is shown schematically at the bottom of Figure 3.

Increasing the eccentricity of the KDE and EE displays has a number of interesting consequences for our descriptions of these stimuli. As two-dimensional images, the contours of these displays become open, overlapping figures. This occurs because extension of the tip of the cone past its base causes the figure to occlude itself. The phenomenal impression of this change in the eccentricity of these displays is that of viewing a rigid cone from an angle. In contrast, our original SKE display consisted of closed, nonoverlapping circles that appear to be a cone viewed nearly head-on. It is worth noting that this change increases the two-dimensional proximal stimulus similarity between KDE and EE displays, and simultaneously decreases the proximal similarity between KDE and SKE displays (an advantage that will be considered in the General Discussion section).

Method

The final sample consisted of twenty-two 5-month-old infants (mean age = 21.6 weeks). Babies were recruited from birth an-

nouncements and other public records, and were drawn from the Charlottesville, Virginia, and the Scarborough, Ontario, communities. Initially, 12 infants were tested in Charlottesville; 10 additional infants, drawn from the Scarborough population, were later added to this sample. These last infants were first intended as practice for training research assistants in the first author's laboratory in Scarborough, and a number of infants were run for this purpose. After training in the habituation procedure it was decided to continue collecting data for this study. At this point, 18 additional infants were run. Five were removed because of fussiness, and 3 because of a general lack of interest in the entire empirical enterprise. These two sets of data were ultimately combined into a single data set, after subjecting them to a wide array of analyses (see Footnote 2) to ensure that there were no important differences between the groups of infants.

Three different stimulus displays were produced. All displays consisted of a series of four rotating, nested ovals. The first stimulus pattern, shown schematically in the top of Figure 3, can be seen as a KDE cone. A distinguishing feature of this display, relative to the displays of Experiments 1 and 2, is that the eccentricity of this apparent cone exceeds 1.0, meaning that the tip of the cone extends past the base, causing self-occlusion. When the display is moving, adults see it as a compelling three-dimensional cone viewed from the side (Proffitt et al., 1992). Again, this display contains both within-contour and between-contour motion. The second stimulus pattern was the SKE described in Experiments 1 and 2, and shown schematically in the middle panel of Figure 3; the only difference was that this pattern included four nested circles, rather than the six of the previous studies. This stimulus contains only between-contour movement, and no within-contour motion. The third display, shown schematically in the bottom panel of Figure 3, was the EE pattern. The EE display was given a comparable eccentricity to that of the KDE display. Again, the EE pattern contains only within-contour movement, with the between-contour information held constant.

All stimuli were generated using the equipment described in Experiment 1. These stimuli were then recorded onto a videotape for later presentation to infants. Again, for KDE and EE displays, the ratio between major and minor axes of the ovals was about 1.25:1. All stimuli appeared as a set of light gray oval contours, presented on a dark gray background.

The apparatus and procedure used to test infants were the same as described in the methods sections of Experiments 1 and 2.² An

² Because these data were collected in two laboratories, there were a number of minor procedural differences between the two sets of infants. The most important distinctions involved the habituation procedure; specifically, the number of trials involved in computing the criterion, and the number of trials required to be regarded as "habituated." For the first 12 infants, the criterion was computed as half of the sum of the first three trials. Habituation was said to have occurred when the sum of any three consecutive trials (after the first trial) was less than the calculated criterion. Thus, the minimum number of trials prior to dishabituation was four. For the second group of 10 infants, the criterion was determined as half of the sum of the first two trials totaling more than 12 s, with habituation occurring when the sum of any two subsequent trials (after the two trials used to set criterion) was less than the criterion. In this case, the minimum number of trials prior to dishabituation was also four. Other distinctions between these infants involved differences in the equipment used, and the actual physical setup of the room. The equipment used for the first set of infants is described in Experiment 1; the equipment for the second set of infants is described in Experiment 2.

infant-control habituation-of-looking time procedure was used for testing discrimination of these stimuli. After habituation to the KDE pattern, infants saw two trials each of the SKE and EE test patterns.³ Half of the infants saw the test display patterns in the order SKE—EE—SKE—EE, while the remaining infants saw the test displays in the order EE—SKE—EE—SKE. A second observer subsequently performed reliability measures on the infants' visual fixations from the videotape recordings. The mean absolute difference in looking time was 0.70 s, with a range from 0.18 s to 1.31 s.

Results and Discussion

The primary data analysis involved determining whether infants discriminated between the KDE, SKE, and EE displays. As in Experiment 1, discrimination was assessed by comparing the amount of time spent looking at the final two habituation trials (KDE), the two SKE test trials, and the two EE test trials, using a two-way ANOVA with the within-subject variable of trial type (KDE, SKE, and EE) and the between-subject variable of test order (SKE/EE vs. EE/SKE).⁴ Figure 2 shows the looking time to the different habituation and test trials. This analysis revealed a significant effect of trial type, $F(2, 40) = 7.82, p < .01$, but no effect for test order, $F(1, 20) = 0.90, ns$, and no interaction between the two, $F(2, 40) = 0.25, ns$.

Subsequent analyses compared the means for the different test trials, using Tukey's HSD test. These comparisons revealed that the KDE and SKE displays did not differ (mean difference = 0.71, *ns*). However, the KDE and EE patterns differed significantly (mean difference = 13.71, $p < .01$), and the SKE and EE patterns also differed significantly (mean difference = 14.42, $p < .01$).

Although the results from this study suggest that infants perceived the KDE pattern as similar to the SKE pattern, and the EE display as dissimilar to the KDE pattern, there is an alternative explanation for these results. Again, it is possible that the EE display was inherently more interesting to infants than the SKE pattern. Experiment 4 tests this hypothesis.

Experiment 4: Looking Times to SKE and EE Displays in Novel Orientations

Experiment 4 assessed whether infants' recovery to the EE display resulted from a general preference for that pattern, relative to the SKE display. Again, if the EE display is inherently more interesting than the SKE display, the amount of time spent looking at the EE display when presented without a prior habituation phase should exceed the amount of time spent looking at the SKE pattern.

Method

The final sample of participants consisted of twelve 5-month-old infants (mean age = 21.9 weeks). Three additional infants were excluded because of computer error (1), failure to get reliability (1), and experimenter error (1). Babies were recruited from the Scarborough, Ontario, community.

The stimulus displays used in this experiment consisted of the SKE and EE displays described in Experiment 3, using the experimental design described in Experiment 2. The apparatus and pro-

cedure were identical to that described in Experiment 2. The mean absolute difference in looking time between the two observers was 0.42 s, with a range from 0.18 s to 0.61 s.

Results and Discussion

We assessed whether infants looked preferentially to either of the SKE or EE displays by comparing the looking time to the three SKE and three EE trials. This comparison was accomplished using a three-way ANOVA, with the within-subject variables of trial type (SKE or EE) and repetition (first, second, or third presentation), and the between-subject variable of order (SKE/EE vs. EE/SKE). This analysis failed to find any significant main effects or interactions. Most important, and as expected, infants' mean looking time to the SKE display (10.48 s) did not differ from the mean looking time to the EE display (10.85 s), $F(1, 10) = 0.01, ns$. Given this finding, it seems unlikely that the differential responding between the SKE and EE test trials observed in Experiment 3 resulted from the EE display being inherently more interesting to infants.

General Discussion

Taken together, these experiments provide compelling evidence that 5-month-old infants, like adults, are sensitive to the presence of between-contour motion information in KDE and SKE displays, but are relatively insensitive to the within-contour motion that accompanies KDE and EE displays. Proffitt et al. (1992) convincingly demonstrated that it is the presence of between-contour motion that leads to a strong percept of three-dimensional form in adults. Likewise, it is tempting to hypothesize that infants are similarly sensitive to the implied three-dimensional form of these displays.

The idea that infants perceive depth and three-dimensional form is a notoriously difficult claim to justify; however, in many ways our results support such an assertion. For example, consider the effects of changing the eccentricity of the KDE and EE displays relative to the SKE display, as in Experiments 3 and 4. One important consequence of this variation is that it increases the two-dimensional physical (proximal) similarity between KDE and EE displays. Both KDE

³ A series of analyses compared aspects of the habituation procedures for these two groups. Specifically, a one-way ANOVA compared these two groups on the mean number of trials to habituate, the length of the initial two visual fixations during habituation, the total length of visual fixation during habituation, the average length of visual fixation per trial, and the subsequent reliability coding of these infants. None of these analyses was significant, indicating that the minor procedural differences did not affect gross characteristics of infants' looking behavior.

⁴ Again, to ensure that no differences existed between the two sets of infants, an initial analysis included a factor differentiating between both sets. This variable failed to produce a reliable main effect, nor did it interact with any of the other variables. Because there were no reliable differences between these sets of infants (see Footnote 3), all data were collapsed across the two groups, and the analyses were recalculated. The results of this subsequent analysis are reported in the text.

and EE patterns now consist of open, overlapping oval contours—essentially, this is the same two-dimensional stimulus pattern. In contrast, the change in eccentricity decreases the two-dimensional similarity between KDE and SKE displays. As opposed to the KDE (and EE) display, the SKE pattern consists of closed, nonoverlapping circles. If infants were responding to some obvious (or not-so-obvious) aspect of the two-dimensional structure then there should have been significant dishabituation to the SKE form and no recovery to the EE display; instead, we saw the reverse pattern. In the same vein, in both Experiments 1 and 3, KDE and SKE patterns contained two-dimensional patterns that were dissimilar. KDE displays consisted of ovals, and SKE displays were made up of circles. Yet the infants perceived these displays as similar.

There is another reason why the results of these experiments indicate infants' appreciation of three-dimensional form. As described earlier, the changing eccentricity of the KDE and EE displays of Experiments 3 and 4 has a strong phenomenological impact on these displays. Specifically, the KDE display appears (at least to adult viewers) as a rotating cone seen from the side. In contrast, the SKE display appears to adults to be a cone seen almost nose on. This difference in phenomenology between the displays has some interesting implications. In previously described work by Kellman (1984; Kellman & Short, 1987), evidence was found for infants' perception of three-dimensional form based on generalization of habituation to a novel orientation of a previously seen object. Failure to dishabituate in these cases, it was argued, could be explained only in terms of an appreciation of the three-dimensional form of the object. Interestingly, Experiment 3 contains an analogous situation to that of Kellman, in that the SKE display can be thought of as a novel orientation of the previously habituated KDE form (a cone). As in Kellman's work, the generalization of habituation across differing views of the cone suggests some understanding of the implied three-dimensional structure of the form.

Seen in this light, our results concur nicely with previous data on infants' perceptions of depth and three-dimensional structure as specified by motion information. Yonas and Granrud (1985), for example, review a wealth of data suggesting that kinematic information provides potent information for infants, starting as early as the first few weeks of life. Nevertheless, it is still possible that the infants in our studies demonstrated sensitivity to the depth information in these displays without perceiving the three-dimensional form *per se*. Accordingly, we must remain cautious as to whether infants are actually perceiving the three-dimensional form of these displays. At the very least, however, these results demonstrate infants' sensitivity to those aspects of motion information underlying the perception of three-dimensional form in adults.

One interesting implication of this work involves the relationship between KDE and SKE displays, and motion parallax. Consider, for example, a motion parallax flow field created by movement of a visual display and by the simultaneous movement of random dots on this visual display (e.g., Rogers & Graham, 1979). According to a recent

analysis by Caudek and Proffitt (1993) comparing SKE and motion parallax stimuli, a motion parallax flow field, like a KDE display, can be decomposed into two component transformations. The first component is a common motion in the optical flow field, consisting of the angular displacement between a point within the object of regard and the observer. The second component consists of the motion remaining after subtracting out this common motion of this display. This second component represents the differential velocities of the flow field that are determined by differing depths of object features. This information is equivalent to the SKE transformation. SKE patterns contain only object-relative transformations and are a subset of motion parallax information.

Although both component transformations are necessary to fully characterize the spatial aspects of these displays, the findings of Caudek and Proffitt (1993) suggest that the perceptual derivation of depth magnitude from motion parallax and SKE displays are based on only the object-relative component of the motion parallax flow field. This claim was indicated by the fact that motion parallax and SKE displays received essentially equivalent responses in terms of perceived depth. This finding is conceptually akin to the work investigating KDE and SKE displays (Proffitt et al., 1992), in which the perception of KDE and SKE displays were based primarily on the presence of the information contained within SKE displays. Accordingly, an interesting extension of these results is that infants might treat as equivalent the information in SKE and motion parallax displays; this hypothesis has yet to be tested.

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