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Perception of Kinetic Illusory Contours by Two-Month-Old Infants

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Perception of kinetic illusory contours by 2-month-old infants was explored with sparse random-dot displays depicting an illusory shape against a background. In Experiment 1, 24 infants were habituated to a shape specified by accretion and deletion of background texture and relative motion, and exhibited a novelty preference when presented with luminance-defined familiar and novel shapes. Subsequent experiments explored kinetic cues in isolation. In Experiment 2 ($n = 24$), relative motion information was removed, leaving accretion and deletion of texture and luminance cues, and in Experiment 3 ($n = 24$), only relative motion information was available. In both these experiments the novelty preference obtained in Experiment 1 was replicated. Results from a control condition ($n = 12$) mitigated against the likelihood of an inherent preference for either of the test shapes. These findings reveal an early capacity to perceive shape solely from kinetic information, and suggest a mechanism geared toward spatiotemporal boundary formation that is functional shortly after birth. Theories of development of edge and motion discrimination are discussed.

INTRODUCTION

When we look around us, we perceive a world of coherent, complete objects despite the fact that many objects are partly occluded by other, nearer objects. Our perceptual experience, however, is not one of fleeting shapes that change their boundaries as they (or we) move, but one of segregated objects that maintain their external boundaries from a variety of viewpoints. To perceive segregated objects, an observer must determine in which depth plane each surface resides, relative to the observer, as well as assign each visible contour to its appropriate surface, taking into account occlusion (Nakayama, He, & Shimojo, 1996). A variety of sources of visual information are available in the optic array to support this task (Cutting & Vishton, 1995). Many of these sources (such as binocular disparity and perspective cues) are "static," meaning that they are available independent of object or observer motion, and some traditional perspectives have suggested that the visual system operates primarily on this static information, rather than responding directly to motion (e.g., Titchener, 1909). Perception of depth was assumed to derive from depth cues found in static retinal images, and perception of motion was considered a "higher order" process composed of an integration of a series of static views (Hochberg, 1978).

In contrast to these notions, Gibson (1966, 1979) pointed out that motion in the optic array is the norm, not the exception, because observers and many objects are mobile, and the eyes move almost constantly. Motion, in fact, carries important information for surface segregation. Motion parallax, for example, specifies the relative distances of surfaces (Rogers & Graham, 1979), two-dimensional patterns of motion can define three-dimensional object shape (Wallach & O'Connell, 1953), and accretion and deletion of background texture (i.e., the simultaneous concealing and revealing of a farther surface) is a reliable cue for relative depth (Kaplan, 1969). The present experiments focused on the ability of very young infants to perceive the contours of moving shapes against a background. Recovery of the shapes' contours was possible only with kinetic information, because the surface properties of the shapes and background were matched in terms of luminance, color, texture, and distance from the observer (i.e., depth). These experiments focused on detection of moving shapes because there are strong reasons to suspect that motion is the principal source of information for object segregation early in postnatal life (Kellman & Arterberry, 1998), but at present little is known about how motion contributes to perception of contour. In the present experiments we showed that the ability of very young infants to perceive shape from kinetic information is exceptionally well organized, a claim based on evidence showing the utilization of two distinct motion cues (accretion and deletion of texture, and relative motion) both together (Experiment 1) and independently (Experiments 2 and 3). First, we turn to a consideration of depth perception and motion sensitivity in infants.

Research conducted over the past few decades has found that young infants' depth perception follows a specific developmental trend. Sensitivity to kinetic depth information appears to emerge first, followed by sensitivity to binocular disparity, and then sensitivity to static-monocular, or pictorial, depth cues (Yonas & Granrud, 1985). Motion-carried information appears to be of primary importance to young infants' perception of surface shape and depth. By 1 month of age, for example, infants respond to optical expansion patterns that specify impending collision (Náñez, 1988), and 3-month-olds utilize accretion and deletion of texture as information for object shape in two-dimensional displays (Kaufman-Hayoz, Kaufman, & Stucki, 1986; Lécuyer & Durand, 1998). Four-month-olds appear to perceive three-dimensional object shape from two-dimensional projections of oscillatory and rotational motion (Arterberry & Yonas, 1988; Kellman, 1984; Yonas, Arterberry, & Granrud, 1987), and object unity from the common lateral motion of surfaces that protrude from behind an occluder (Kellman & Spelke, 1983). Not until some time around 4 months or later, however, do infants respond to binocular disparity as information for depth (Braddick et al., 1980; Granrud, 1986) and object shape (Yonas et al., 1987). Finally, sensitivity to pictorial cues as information for depth seems to emerge some time between 5 and 7 months (Granrud, Haake, & Yonas, 1985; Granrud & Yonas, 1984; Granrud, Yonas, & Opland, 1985; Yonas, Granrud, Arterberry, & Hanson, 1986; Yonas, Granrud, & Pettersen, 1985).

Some of these investigations have used stimuli consisting of two-dimensional, dynamic random-dot displays. Random-dot displays, for example, have been used to demonstrate perception of the relative depth of surfaces in 5- and 7-month-olds, who tended to reach more often toward the portion of a two-dimensional display that appeared nearer due to accretion and deletion of texture (Granrud et al., 1984). Perception of surface shape in dense random-dot textures has been demonstrated in 4-month-olds (Johnson & Aslin, 1998) and 3-month-olds (Kaufman-Hayoz et al., 1986). (In dense random-dot textures, an approximately equal number of black-and-white texture elements are randomly dispersed across the stimulus, so that any individual element in the stimulus has a 50% chance of being either black or white.) In the Johnson and Aslin study, 4-month-olds were habituated to a display in which two rod parts underwent lateral motion above and below an occluding box, which itself underwent out-of-phase motion relative to the rod parts. The rod parts, box, and background were all covered with a dense random-dot texture. After habituation to this display, the infants subsequently looked longer at a dense texture display depicting two rod parts separated by a gap, relative to a single, complete rod. Thus, the infants distinguished the rod and box shapes from the background (and appeared to perceive the unity of the rod parts behind the box; cf. Kellman & Spelke, 1983). In the Kaufman-Hayoz et al. study, 3-month-olds were habituated to displays in which a cross or butterfly shape moved against a background. Both shapes and the background were covered by dense random-dot texture. After habituation, the infants looked longer at a novel, luminance-defined shape relative to a familiar shape, demonstrating perception of the motion-defined shapes in the habituation displays.

Perception of contour from motion-carried information in sparse random-dot displays has been found to be robust in adults under a variety of conditions (e.g., Andersen & Cortese, 1989; Hine, 1987; Shipley & Kellman, 1993, 1994; Stappers, 1989), and reports of young infants' shape perception in sparse random-dot displays are beginning to emerge. Johnson and Aslin (1998) devised a computer-generated display in which partly occluded rod and box shapes underwent out-of-phase motion against a background (see previous paragraph). Shapes and background were covered by a "sparse" texture in which approximately 3% of texture elements were white; the rest were black. (In the sparse random-dot textures used in the present report, the majority of stimulus elements were black [about 98.5%] with a small number of white elements [about 1.5%], in like manner to stars against a black sky.) After habituation to this display, 4-month-olds looked longer at two rod parts, relative to a single, complete rod, again implying perception of the rod and box shapes, and the unity of the rod parts. Shape perception in both dense and sparse textures was robust (there was no statistically reliable difference in posthabituation looking-time patterns between the two conditions). Arterberry and Yonas (1988) habituated 4-month-olds to a two-dimensional display in which a random-dot cube, or a partial cube, oscillated about two different axes against a matte black background. The two shapes were not distinguishable in static views. After habituation, the infants were presented with solid versions of the full and partial cubes, and looked longer at the novel stimulus, suggesting three-dimensional shape perception in the random-dot displays from optic flow information.

The present studies sought to extend our knowledge in this area in two ways. First, infants younger than those in previous reports of perception of kinetic contours were tested. Two months has been purported to be the point at which motion discrimination emerges in humans, perhaps due to maturation of cortical processing streams subserving motion perception (see Banton & Bertenthal, 1997; Johnson, 1990; Wattam-Bell, 1991). Therefore, 2-month-olds were observed in the present experiments, to investigate whether infants at this age could employ motion-sensitive mechanisms in the service of shape perception. There are several reasons to predict that motion may define surface shape at this early age: Johnson and Aslin (1995) and Johnson, Cohen, Marks, and Johnson (2001) found that 2-month-olds perceive the unity of both translating and rotating objects in partial occlusion displays, and Arterberry and Yonas (2000) replicated the finding of three-dimensional surface shape from two-dimensional optic flow with a sample of 2-month-olds. A second advance represented by the present experiments is rooted in the use of sparse texture density, rather than dense texture. Andersen and Cortese (1989) reported that adults' contour perception was weakened with decreasing dot densities, suggesting that the limits of infants' sensitivity to kinetic information likewise can be explored with sparse texture displays.

The present experiments examined the robustness of young infants' shape perception under what might be expected to be more challenging conditions relative to past research using more dense textures. Two-month-old infants were presented with computer-generated displays in which illusory contours were made visible by kinetic cues, but would not be available from static information. These displays consisted of surfaces undergoing motion against a background. Both the surfaces and the background were covered with a sparse random-dot texture, such that if the surfaces were to be stationary, they would be camouflaged (see Figure 1). When in motion, however, the shapes were readily apparent. This situation contrasts sharply with shape perception in everyday scenes, because object contours in the real world typically are specified to the observer by physical discontinuities in luminance, color, depth, and/or texture, in addition to motion. Unlike dense random-dot textures, which contain texture elements (and therefore motion gradients, or discontinuities) at the locations of visible edges, sparse textures have no physical gradients across any contours that nevertheless may be evident to the viewer. In other words, they are illusory, but as was demonstrated in Experiments 1 through 4 of the present study, infants and adults readily discerned the moving shapes in the textures.

The contours under consideration in the present article are not claimed to be perceptible under the same circumstances, and certainly not with the same neural mechanisms, as more well-known illusory contours such as those evident in the Kanizsa triangle, which do not rely on motion. Nevertheless, the definition of illusory contour provided in this Introduction is consistent with many reviews on the topic (e.g., Lesher, 1995; Parks, 1984; Meyer & Petry, 1987; Spillman & Dresp, 1995). Moreover, the term "illusory" (or "subjective") has been used frequently to describe phenomena similar to those under investigation in the present experiments, in studies of adults' perception of kinetic con-

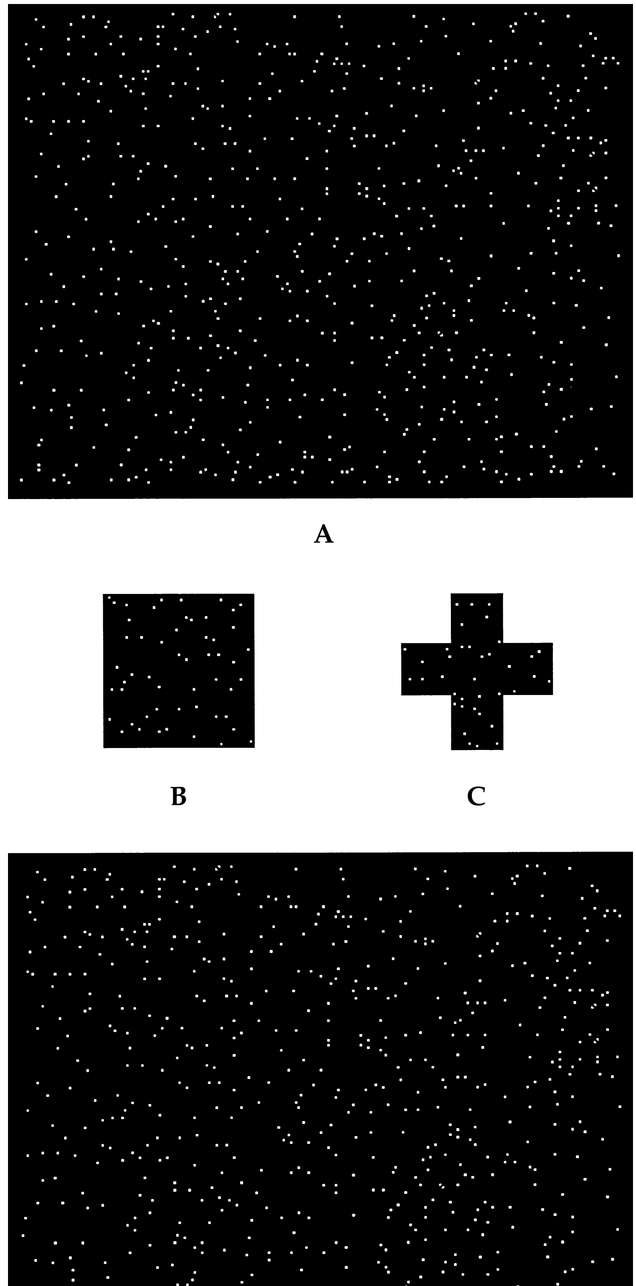

Figure 1 Displays used in the present experiments. (A) Background of displays in Experiments 1 through 4. (B) Illusory square from Experiment 1. (C) Illusory cross from Experiment 1. When the illusory shapes were stationary they were camouflaged and therefore invisible, because both shapes and background were composed of the same sparse texture. This is illustrated in (D), in which the illusory square and cross are placed against the background (the square is on the left; the cross is on the right). The contours of the shapes were prominent, however, when they moved.

tours (e.g., Andersen & Cortese, 1989; Hine, 1987; Prazdny, 1986).

An habituation paradigm was used in the present experiments. Infants were first presented with a kinetic illusory shape (either a square or a cross) repeatedly until looking declined to a preset criterion, described subsequently. After this decline in looking times (i.e., habituation), the infants viewed two new test displays with luminance-defined (gray) shapes, either a square or a cross. One shape matched the contour of the habituation stimulus, and the other was novel. We reasoned that if infants were able to detect the kinetic illusory contour during habituation, they would look longer during test at the novel shape, given that infants typically exhibit novelty preferences after a period of habituation to a single stimulus (Bornstein, 1985).

EXPERIMENT 1

The displays utilized in Experiment 1 consisted of either an illusory square or cross shape (Figure 1). Both shapes and the background were composed of a sparse random-dot texture. Because the shapes and background were composed of the same texture, the shapes' contours would be camouflaged in the absence of motion. As the shapes moved, however, they were clearly discernible.

Method

Participants. The final sample consisted of 24 term infants (14 female; M age = 64.4 days, SD = 2.87 days). Nine additional infants were observed, but not included in the sample due to excessive fussiness (5) or sleepiness (4). The infants were recruited by hospital visits and follow-up telephone calls. The majority of the infants were from Caucasian, middle-class families. Parents were paid a nominal sum for their participation.

Apparatus. An Amiga 3000 computer and a 76-cm monitor were used to generate the displays. Two observers viewed the infant through small peepholes cut into two black panels that extended 47 cm from the sides of the monitor.

The computer presented the stimulus displays, stored each observer's data, calculated the habituation criterion for each infant, and changed displays after the criterion was met. The computer also recorded how long the infant looked at each display, according to the observers' judgments. These judgments were entered via handheld buttons, connected to the computer's mouse port. Observers were blind to the stimulus on the screen at any given time, and to each infant's experimental condition (which was assigned randomly by the computer).

Stimuli. The displays contained a background consisting of a 44.5 cm × 40.6 cm array of 45,549 dots (in a 241 × 189 array), subtending 24.0° × 22.1° visual angle at the infant's 100-cm viewing distance. Approximately 1.5% of the dots were white (70.3 cd/m^2), randomly distributed over the array. The remainder of the dots were black (.3 cd/m^2). Each dot subtended approximately 6′ × 7′ visual angle. This produced a sparse random-dot texture (Figure 1A). Habituation displays consisted of a 4-s animation (30 frames per second, run as a loop) depicting a square or a cross, both covered by sparse random-dot texture, and moving in a square path centered around the midpoint of the display. Each shape measured 16.2 cm × 15.4 cm (9.2° × 8.8°); four sectors measuring 5.8 cm × 5.3 cm (3.3° × 3.0°) were cut out of the square to produce the cross. The path of motion was defined by a square measuring 11.8 cm (6.7°) per side. A shape took 1 s to move from corner to corner of the path; thus its velocity was 11.8 cm (6.7°) per second. After habituation, the infants viewed moving square and cross displays in which the shape was a solid gray (15.0 cd/m^2). Test shapes were of the same dimensions as the habituation shapes, were moved in the same pattern and at the same rate, and were presented against the same textured background.

Twenty-four infants were habituated to one of the two habituation displays. After habituation, all infants viewed the solid square and cross test displays, presented three times each in alternation. In each group of 12 infants, 6 viewed the solid cross first after habituation, and 6 viewed the solid square first (order was determined randomly by the computer).

Procedure. The infants were tested individually in a darkened room, each placed in an infant seat approximately 100 cm from the display monitor. The habituation display was presented until the infant met the habituation criterion. This criterion was defined according to the common "infant-control" procedure (Horowitz, Paden, Bhana, & Self, 1972) as a decline in looking time during three consecutive trials, adding up to less than half the total looking time during the first three trials. Infants who had not habituated after 12 minutes (n = 3 across all experiments in this report) were moved on to the test displays.

Timing of each trial, during both habituation and test, began when the infant fixated the screen after display onset. Each observer indicated independently how long the infant looked at the display by pressing a separate button as long as the infant fixated the screen, and releasing the button when the infant looked away. (For 29 of the infants across Experiments 1–3, only one observer was available due to scheduling conflicts.) An individual trial was terminated when both observers released their buttons for two overlapping seconds. At this point, the screen was turned off by the computer, and the next display appeared 2 s later.

When looking times to the habituation display declined to criterion, the computer changed from habituation to test displays. The two test displays were seen three times each in alternation, for a total of six posthabituation trials.

Results and Discussion

Looking times were calculated by averaging the two observers' judgments for each test trial. Interobserver agreement was high for those infants for whom two observers were available (mean Pearson $r = .97$ across all experiments). The looking time data in some cells were positively skewed, and all data were subjected to a logarithmic transformation prior to analysis. (The data presented in Figures 2, 4, and 6 and in the text are based on raw scores.) Data were first analyzed for differences in habituation time as a function of shape seen during habituation (square versus cross); there were no significant differences between habituation times in any of the three experiments, all Fs < 3.0, *ns*.

Figure 2 shows posthabituation looking time preferences for each infant in Experiment 1, computed as looking time to the gray square test display divided by total looking to both test displays. Of the 24 infants, 21 exhibited a novelty preference, $z = 3.74$, $p < .001$, Wilcoxon matched pairs test, looking longer overall at the novel shape. Of the 12 infants habituated to the illusory square, 11 looked longer at the solid cross during test, relative to the solid square, $z = 2.98$, $p < .01$. Conversely, 10 of the infants who were habituated to the illusory cross looked longer at the solid square, $z = 2.12$, $p < .05$.

Looking times during the six posthabituation test trials were examined with a 2 (habituation shape) × 2 (gender) × 2 (order of test display presentation: square or cross first) × 2 (display: familiar versus novel) × 3 (trial: first, second, or third test trial block) mixed ANOVA. The only significant main effect was for that of display, $F(1, 16) = 30.82$, $p < .001$, the result of longer looking at the novel shape during test (*M* looking at the novel shape = 85.1 s, *SEM* = 11.3 s; *M* looking at the familiar shape = 43.7 s, *SEM* = 7.9 s). There was a significant interaction between display and gender, $F(1, 16) = 7.36$, $p < .05$, the result of stronger novelty preferences by females, $F(1, 16) = 45.54$, $p < .001$, relative to males, $F(1, 16) = 3.22$, $p = .09$ (these posthoc analyses were computed by simple effects tests). There was also a significant interaction between display and shape, $F(1, 16) = 7.99$, $p < .05$, the result of stronger novelty preferences after habituation to the illusory square, $F(1, 16) = 30.08$, $p < .001$, relative to the illusory cross, $F(1, 16) = 4.45$, $p = .05$.

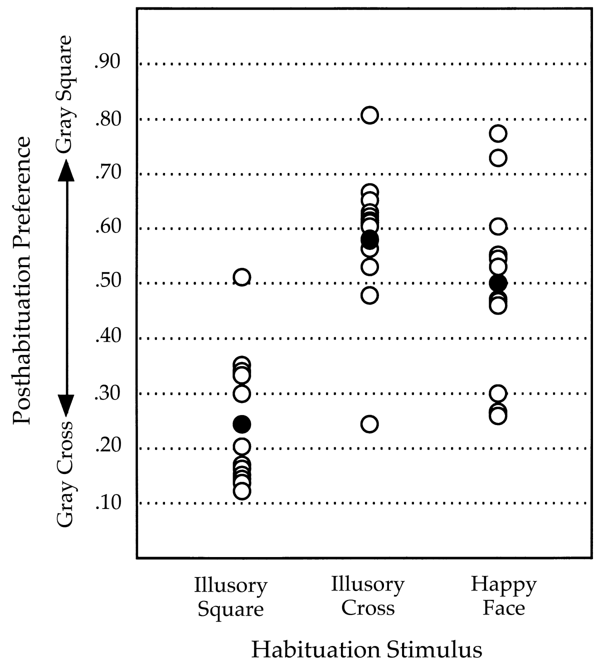

Figure 2 **Infants' test display preferences in Experiment 1, as a function of proportion of looking to the gray square. Open circles represent individual participants, and filled circles represent group means. The majority of infants habituated to the illusory square preferred the gray cross, whereas the majority of infants habituated to the illusory cross preferred the gray square. Infants habituated to a happy face exhibited no consistent test display preference across the group.**

The novelty preference main effect was predicted, but the two significant interactions were unexpected. There are several possible accounts for these interactions. It could be, for example, that females are better at detecting kinetic contours than are males early in postnatal development, and that the novelty preference that was predicted after habituation to the illusory cross was compromised by an inherent preference for a cross shape relative to a square (or that the illusory square shape was easier to detect). We believe a simpler account is more likely, however. Inspection of Figure 2 reveals that a single infant (male) in the illusory cross condition exhibited dramatically long looking toward the gray cross during test (for unknown reasons), and this may have had an unusually drastic impact on the resulting analysis (i.e., spurious effects of gender and shape).

Support for this simpler interpretation comes from additional analyses and data. Notably, there was a reliable novelty preference on the part of the remaining males in the sample, $t(8) = 3.23$, $p < .05$. As a check on the likelihood of an inherent preference for either of the test displays, an additional control group of twelve 2-month-olds (6 females; *M* age = 66.2 days, *SD* = 7.13) were presented with the gray square and gray cross test displays after habituation to a 17.5 × 15.5 cm (9.9° × 8.8°) yellow happy face, presumably unrelated to either test shape. The happy face moved back and forth at a rate of 5.8 cm/s (3.3°/s) through 23.0 cm (13.0°) in an 8-s looped animation. Other aspects of the experimental design were identical to those described previously. Infants in this control group exhibited no consistent preference for either test display: Six infants looked longer at the gray square test display, and 6 looked longer at the cross (see Figure 2); there was no reliable looking time difference, $t(11) = .07$, *ns* (*M* looking at the gray square = 35.8 s, *SEM* = 5.3 s; *M* looking at the gray cross = 41.4 s, *SEM* = 10.2 s). It seems plausible, therefore, that the single male participant in the illusory cross condition who had an extreme posthabituation preference for the cross produced the unexpected pattern of interactions. Nevertheless, the possibility of gender differences or differences in discriminability or preferences between shapes could not be ruled out completely on the basis of the results of Experiment 1, and we return to these issues in the following two experiments.

In sum, infants who were habituated to a square or cross kinetic illusory shape, and subsequently presented with luminance-defined shapes that were either identical or novel relative to the habituation contour, tended to prefer the novel shape. Infants in a control condition showed no preference for either test display. These results imply that by 2 months of age, infants can perceive kinetic illusory contours under some conditions. These results do not indicate, however, how the infants were able to perceive the shapes. The shapes' contours were specified by two classes of motion-based cue, accretion and deletion of texture at the edges orthogonal to the shapes' motion, and relative motion of the dots contained within the shape and the dots in the background (i.e., motion shear at the edges parallel to the shapes' motion, and the common, rigid motion of the configuration of dots within the shapes' boundaries). Experiments 2 and 3 were designed to investigate the relative potency of these cues' contributions to shape perception by presenting them in isolation.

EXPERIMENT 2

To more fully explore the question of the precise kinetic cues used by the infants in Experiment 1 to perceive illusory contours, a group of 2-month-olds was habituated to a display in which a moving black square or cross shape was presented against the same sparse texture background as that employed in Experiment 1 (see Figure 3, in which the shapes are presented against the background). The shapes were the same dimensions as in Experiment 1, and moved in the same pattern and at the same rate. Unlike Experiment 1, however, these shapes were black and contained no texture elements, creating a luminance gradient, relative to the background, in addition to the motion gradient provided by accretion and deletion of texture. (The percept of motion was produced via a pattern of background dots "blinking" on and off in a structured manner. This phenomenon is discussed in more detail in the General Discussion.) The question under investigation, therefore, was whether 2-month-olds could detect a moving shape defined by accretion and deletion of texture (available in the Experiment 1 stimuli) along with a luminance difference relative to the background (not available in Experiment 1), but absent relative motion. If 2-month-olds were able to do so, we hypothesized that the infants would exhibit a reliable preference for the novel shape during test.

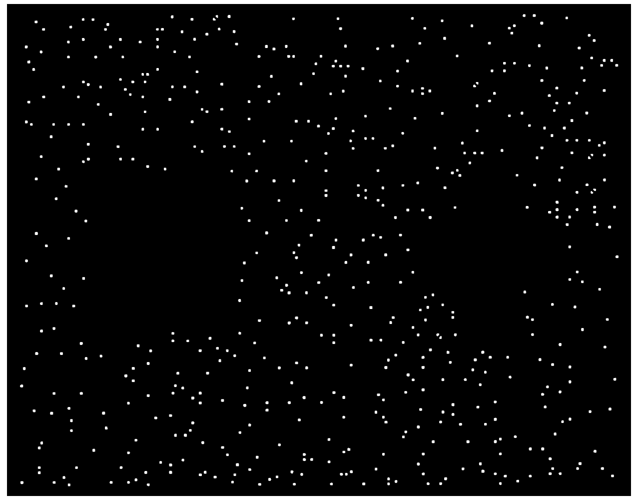

Figure 3 The black square and black cross shapes from Experiment 2 are placed against the background to illustrate the lack of clear contours when the stimuli are stationary (the square is on the left; the cross is on the right). The two shapes are discriminable by adults, however, on the basis of static information (Experiment 4).

Method

Participants. The final sample consisted of 24 term infants (12 female; *M* age = 63.0 days, *SD* = 9.1 days). Eight additional infants were observed but not included in the sample due to excessive fussiness (4) or sleepiness (4). The infants were recruited from the same population and in the same manner as described in Experiment 1.

Apparatus, stimuli, and procedure. Details were identical to those described in Experiment 1, except the moving shapes viewed during habituation were entirely black.

Results and Discussion

Figure 4 shows posthabituation looking time preferences for each infant in Experiment 2, computed as looking time to the gray square test display divided by total looking to both test displays. Of the 24 infants, 19 exhibited a novelty preference, $z = 2.69$, $p < .01$, looking longer overall at the novel shape. Of the 12 infants habituated to the black square, 9 looked longer at the solid cross during test, relative to the solid square, $z = 2.12$, $p < .05$. Conversely, 10 of the infants who were habituated to the black cross looked longer at the solid square, $z = 1.57$, $p = .12$.

Looking times during the six posthabituation test trials were examined with a 2 (habituation shape) × 2 (gender) × 2 (order of test display presentation) × 2 (test display) × 3 (trial) mixed ANOVA. There were significant main effects of display, $F(1, 16) = 7.23$, $p < .05$, the result of longer looking at the novel shape during test (*M* looking at the novel shape = 31.9 s, *SEM* = 3.4 s; *M* looking at the familiar shape = 23.0 s, *SEM* = 3.9 s), and of trial, $F(2, 32) = 3.32$, $p < .05$, resulting from a decline in looking across test trials. There were no other significant effects.

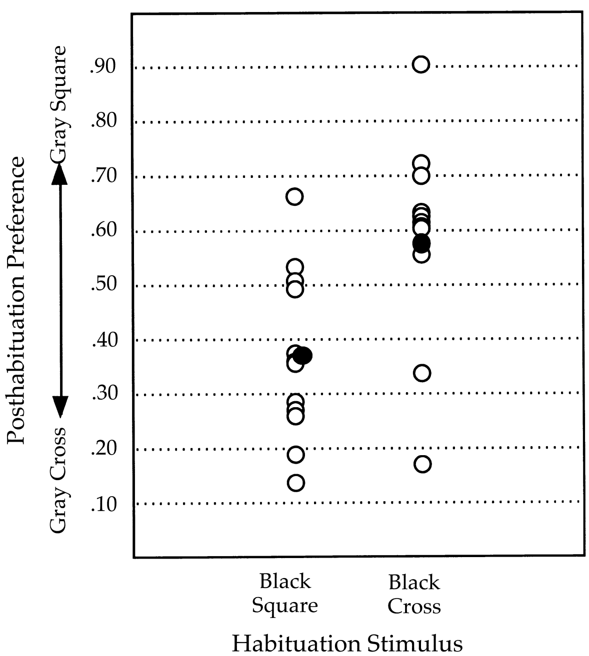

Figure 4 Infants' test display preferences in Experiment 2, as a function of proportion of looking to the gray square. Open circles represent individual participants, and filled circles represent group means. The majority of infants habituated to the black square preferred the gray cross, whereas the majority of infants habituated to the black cross preferred the gray square.

Infants who viewed black shapes defined by both luminance and accretion and deletion of texture looked longer at a novel stimulus during test, indicating perception of the shape during habituation. There were no differences as a function of either gender or habituation shape, implying that the interactions obtained in Experiment 1 were circumstantial and the result of the sometimes large variations in looking times that are characteristic of samples of very young infants.

The positive outcome of this experiment is not surprising, given the robust performance of infants in Experiment 1, and the addition of luminance information in Experiment 2 to define the shape. A more stringent test of the contribution of kinetic information to young infants' illusory contour perception was provided in Experiment 3, in which luminance information specifying shape was removed.

EXPERIMENT 3

Experiment 3 continued the investigation of the cues used by the infants in Experiment 1 to perceive kinetic illusory contours. A group of 2-month-olds was habituated to a display in which a moving square or cross shape was presented against the same sparse texture background as that employed in Experiments 1 and 2. The shapes were the same dimensions as in Experiments 1 and 2, and moved in the same pattern and at the same rate. In Experiment 3, these shapes were composed of the same dot configuration as that contained in the square and cross shapes of Experiment 1, but there was no accretion and deletion of background texture (cf. Cunningham, Shipley, & Kellman, 1998a). In other words, these "dot square" and "dot cross" shapes were defined by the grouping of dots moving against the background, and the background dots remained visible through the shapes (Figure 5); the dots blended with the background when stationary (see Experiment 4). The question under investigation, therefore, was whether 2-month-olds could detect a moving shape specified solely by relative motion (motion shear and the common, rigid motion of the dot configuration), in the absence of usable stationary information (e.g., luminance) and accretion and deletion of texture. If 2-month-olds were able to do so, we hypothesized that the infants would exhibit a reliable preference for the novel shape during test.

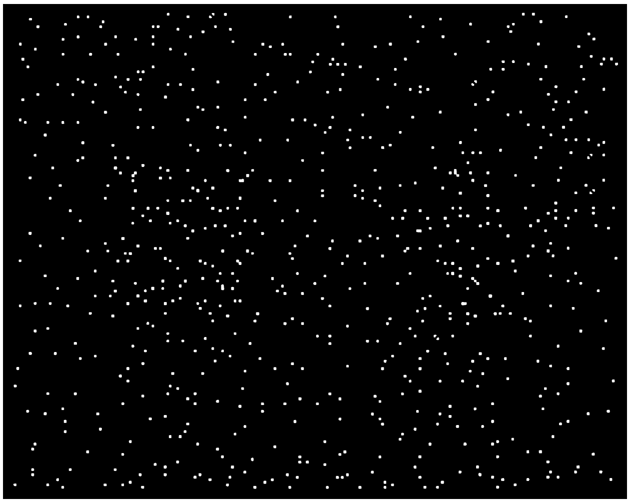

Figure 5 The dot square and dot cross shapes from Experiment 3 are placed against the background to illustrate the lack of clear contours when the stimuli are stationary (the square is on the left; the cross is on the right). The two shapes are not discriminable by adults on the basis of static information (Experiment 4).

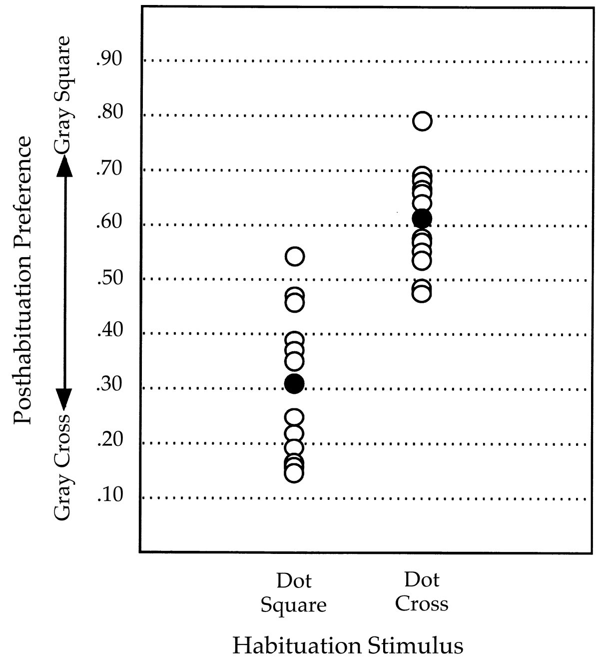

Figure 6 Infants' test display preferences in Experiment 3, as a function of proportion of looking to the gray square. Open circles represent individual participants, and filled circles represent group means. The majority of infants habituated to the dot square preferred the gray cross, whereas the majority of infants habituated to the dot cross preferred the gray square.

Method

Participants. The final sample consisted of 24 term infants (7 female; *M* age = 66.2 days, *SD* = 6.3 days). Six additional infants were observed but not included in the sample due to excessive fussiness (4) or sleepiness (2). The infants were recruited from the same population, and in the same manner as described in Experiments 1 and 2.

Apparatus, Stimuli, and Procedure. Details were identical to those described in Experiment 1, except the moving shapes viewed during habituation were composed of the same dot configuration as that contained in the moving shapes in Experiment 1 and they did not occlude background texture.

Results and Discussion

Figure 6 shows posthabituation looking time preferences for each infant in Experiment 3, computed as looking time to the gray square test display divided by total looking to both test displays. Of the 24 infants, 21 exhibited a novelty preference, $z = 4.03$, $p < .001$, looking longer overall at the novel shape. Of the 12 infants habituated to the dot square, 11 looked longer at the solid cross during test, relative to the solid square, $z = 2.82$, $p < .01$. In contrast, 10 of the infants who were habituated to the dot cross looked longer at the solid square, $z = 2.82$, $p < .01$.

Looking times during the six posthabituation test trials were examined with a 2 (habituation shape) × 2 (gender) × 2 (order of test display presentation) × 2 (test display) × 3 (trial) mixed ANOVA. There was a significant main effect of display, $F(1, 16) = 41.23$, $p < .001$, the result of longer looking at the novel shape during test (*M* looking at the novel shape = 51.8 s, *SEM* = 8.0 s; *M* looking at the familiar shape = 30.1 s, *SEM* = 5.5 s). There were no other reliable effects.

Infants who viewed dot shapes defined by relative motion (motion shear and common, rigid dot motion relative to the background) looked longer at a novel shape than at a familiar shape during test, implying perception of the contours of the dot square and dot cross during habituation. As in Experiment 2, there were no reliable effects involving either gender or habituation shape, providing further evidence against a difference in performance as a function of gender or ease of detection of either shape, and evidence in favor of the suggestion that the interactions obtained in Experiment 1 were spurious. Experiment 3 provided the strongest evidence in the present report for the ability of young infants to perceive motion-based contours, because the information specifying the contours was relatively impoverished: Only relative motion was available to specify form, because accretion and deletion of texture had been removed.

EXPERIMENT 4

Experiment 4 probed adults' ability to detect the kinetic illusory contours shown to the infants in Experiments 1 through 3. In addition, the adults were shown static versions of the displays, to gauge the potency of stationary information in specifying contour.

Method

Participants. Ten undergraduate volunteers served as participants. All had normal or corrected-to-normal vision, and were blind to the hypothesis under investigation.

Apparatus, stimuli, and procedure. The same computer and monitor as in Experiments 1 through 3 were used to generate and present the stimuli. Adult participants were tested individually under the same conditions as those used with the infants (i.e., in a darkened room and seated the same distance from the monitor). In this experiment, a method developed by Shipley and Kellman (1993, 1994) was adapted. Participants were told that they would be seeing either a square or a cross shape against a background, and that their task was to report which shape was present. Each participant viewed 12 displays, 6 in which the shape was stationary (i.e., illusory square, illusory cross, black square, black cross, dot square, and dot cross) and 6 in which the shape moved (i.e., the 6 displays shown to infants in Experiments 1 through 3). For the 6 stationary displays, the shape was placed in one of the four corners of the display, and participants were asked to report which corner contained the shape (in addition to which shape it was). Participants were told to guess if they could not detect the shape and its location readily in the static displays, and were prompted for a response if they had not given one within approximately 30 s. Order of display presentation was randomized, with the single constraint being that all stationary displays were viewed first. Location of shape within the stationary displays was also randomized.

Results and Discussion

Figure 7 shows the number of adult participants who reported correctly the shape and its location in the stationary displays, and the shape only in the motion displays. The shapes were readily detected in the

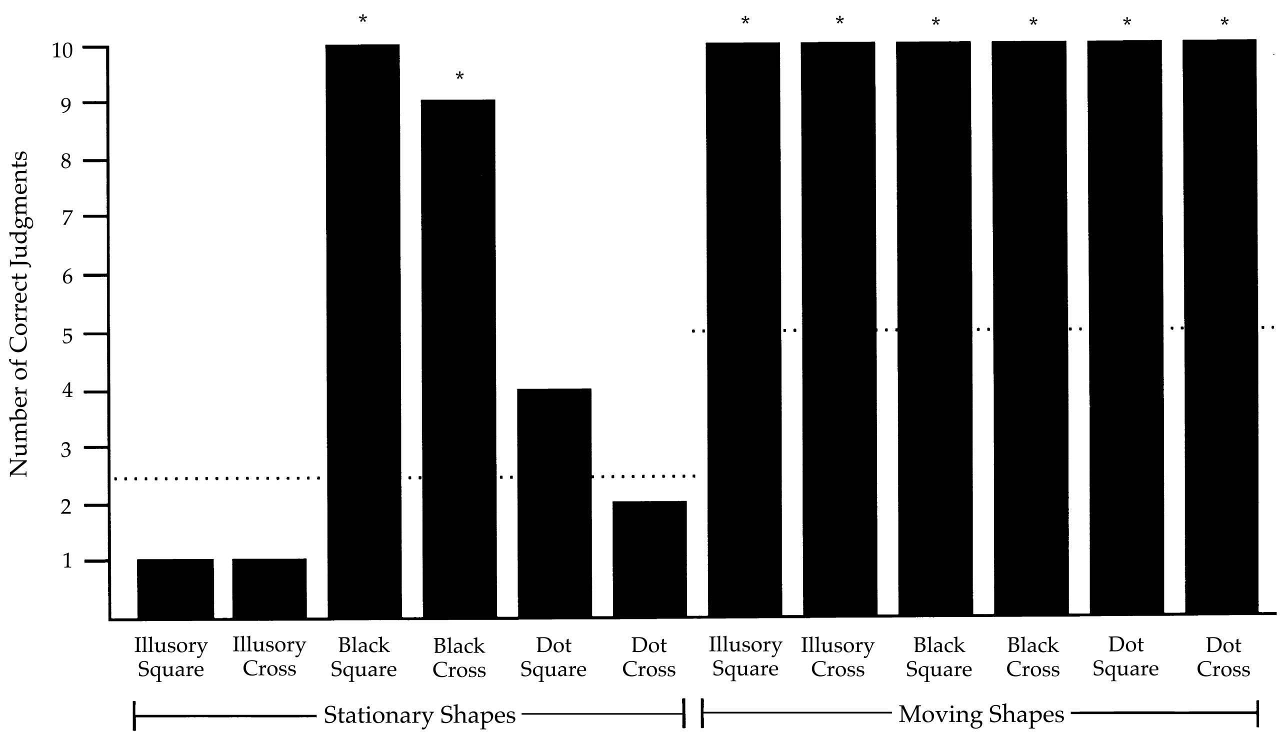

Figure 7 Adults' judgments in Experiment 4. Adults reported correctly which shape was present in all motion displays, all outcomes better than chance (50%) as revealed by binomial tests. In contrast, performance was not different relative to chance (25%) in the stationary displays, except when the shapes were black (and thus visible from luminance information). This latter result indicates that there was little or no static information available in the kinetic illusory and dot displays to contribute to contour discrimination. *Significantly different from chance, binomial test.

motion displays, but only the black shapes were detected at a level better than chance (as revealed by binomial tests) in the stationary displays. These results indicate that reliable static information specifying form was available for the black shapes, whose contours were suggested by luminance information, but that the illusory and dot shapes were effectively camouflaged in the absence of motion. The infants in Experiments 1 and 3, therefore, appeared to have relied exclusively on kinetic information in perceiving the contours in these displays.

GENERAL DISCUSSION

In this study, evidence was obtained for perception of kinetic illusory contours in 2-month-old infants and adults. In Experiment 1, after habituation to either an illusory cross or an illusory square infants looked longer at a solid, luminance-defined square or a solid cross, respectively, suggesting abstraction of the illusory shape in the habituation display. A control group demonstrated no consistent preference for either solid shape. Initial evidence suggesting a gender difference in performance (favoring females) was not replicated in either of the two subsequent experiments. Experiments 2 and 3 explored more precisely the kinds of kinetic information used by the infants to detect the shapes. The infants appeared to perceive the shapes from both accretion and deletion of texture (in conjunction with luminance information) and relative motion (motion shear and common, rigid dot motion). The adults showed a similar pattern of shape discrimination with these motion displays, but failed to detect the shape in stationary displays unless it was luminance defined (i.e., black), suggesting that the infants did not have access to static information in Experiments 1 and 3.

The evidence across the first three experiments revealed a remarkable facility of very young infants to organize underspecified stimuli into coherent percepts, and motion was the key to this organization. Research on the emergence of sensitivity to different types of motion in infancy has revealed several distinct processing mechanisms that appear to develop at different rates, and may reflect nonuniform cortical development in early infancy (Banton & Bertenthal, 1997). At present little is known about the development of utilization of motion in perceptual tasks, although more is known about the development of young infants' sensitivity to motion and other cues to surface segregation, the relative and absolute distances of surfaces, and so on (for a review, Kellman & Arterberry, 1998). The extent to which infants are sensitive to temporal modulation in general to segregate surfaces is also unclear. In the only extant study that has explored this question, Jusczyk, Johnson, Spelke, and Kennedy (1999) probed 4-month-olds' utilization of synchronous changes over time to perceive the unity of a partly occluded object, by embedding small lights in a rod whose center was hidden by a rectangular box, and using computer-generated stimuli. The visible rod parts underwent synchronous changes in color or brightness (e.g., flashing). Jusczyk et al. tested perception of object unity in both static and motion displays. The infants did not perceive unity in any static display, but readily responded to unity when the rod parts underwent common motion. These findings provide further evidence that in the larger class of synchronous changes over time, motion has a special status in infants' perceptual organization.

In contrast to the robust detection of kinetic shapes by 2-month-olds in the present experiments, edge perception in static displays has been found to undergo a more protracted developmental profile, including perception of static illusory contours. Neonates can perceive luminance-defined edges, even with relatively poor visual resolution (see Slater, 1995), but several lines of research point to restrictions in young infants' ability to organize stationary information into coherent percepts of occlusion. First, Kellman and Spelke (1983; see also Jusczyk et al., 1999) reported that 4-month-olds failed to perceive the unity of a partly occluded rod when it was stationary, but perception of object unity was especially reliable when the rod moved (Johnson & Aslin, 1995, 1996; Kellman, Spelke, & Short, 1986). The earliest age at which infants have been found to perceive the unity of a stationary partly occluded object is 6.5 months (Craton, 1996). A similar pattern of results comes from investigations of infants' perception of static illusory contours. There is some evidence that 3- and 4-month-olds can perceive illusory contours in a Kanizsa square, but this evidence is somewhat mixed (Ghim, 1990); other estimates narrow the time of emergence to later than 5 months (Bertenthal, Campos, & Haith, 1980; Csibra, Davis, Spratling, & Johnson, 2000). These findings, and others, have prompted speculations that infants younger than 6 months are "edge insensitive" (Kellman, 1993; Kellman & Arterberry, 1998; Kellman & Shipley, 1991), meaning that they are unable to link edges across a spatial gap (either a real gap imposed by an occluder, or a virtual gap in an illusory contour display) on the basis of static information. This timing, interestingly, fits well with the notion that sensitivity to pictorial, static depth information also develops after 5 months of age (Yonas & Granrud, 1985). The finding of edge insensitivity in young infants is surprising, however, given that edge information (e.g., orientation) is represented in the earliest stages of cortical visual processing, even including cells that are responsive to both luminance-defined and illusory contours (Peterhans & von der Heydt, 1991). Precise mechanisms of development of edge sensitivity beyond the descriptive level are unknown at present, and merit further investigation.

The results of the present experiments, and a recent, related report by Curran, Braddick, Atkinson, Wattam-Bell, and Andrew (1999), reveal a functional second mechanism of contour perception—one that does not rely on static information but instead guides early perceptual organization from kinetic cues. This outcome is consistent with a large body of literature that underscores the importance of texture-based cues in adults' perception of dynamically defined shapes (e.g., Andersen & Cortese, 1989; Gibson, Kaplan, Reynolds, & Wheeler, 1969; Hine, 1987; Kaplan, 1969; Stappers, 1989). In a series of reports, Shipley and Kellman (1993, 1994, 1997) described a process called spatiotemporal boundary formation, or SBF, which supports dynamic edge perception from abrupt changes at the edges of visible shapes. Accretion and deletion of texture provides an example. At the leading edge of a moving form, background texture elements disappear, as other elements appear at the form's trailing edge. In computer-generated displays (such as in the present study), these events are discrete and abrupt. In the moving black shape displays, for example, a convincing percept of a moving form was produced strictly by a pattern of dots that disappeared and reappeared, in the absence of actual moving elements.

SBF, however, is not limited to appearance and disappearance of background texture elements, which are tantamount to changes in luminance. Abrupt changes in the color, orientation, and location of individual texture elements can also support SBF (Shipley & Kellman, 1993, 1994). Shipley and Kellman have suggested that SBF may be part of a more general perceptual mechanism that segregates surfaces based on motion information (Cunningham, Shipley, & Kellman, 1998b; Shipley & Kellman, 1997). The results of the present study imply that such a mechanism is functional early in ontogeny, and invite future research to explore more fully the conditions under which SBF contributes to young infants' surface perception. Other than the results of Experiment 2 of the present report, little is known about how general SBF may be in visual development, but given the wide range of conditions under which it is evident in adults, it seems likely that other kinds of SBF will specify shape to infants as well. Shipley and Kellman (1994), for example, described a "unidirectional" transformation of background texture dots in which a small group of dots is a different color or luminance relative to the others. When the configuration of dots that is colored is made to change (e.g., the leftmost dots in the group change to the background color, and the group of background dots next to the group at right simultaneously changes to match the group), this can give rise to a percept of a moving shape. One interpretation of this moving shape is consistent with a transparent surface against the background. A recent report of transparency perception in infants (Johnson & Aslin, 2000) provides additional reasons to speculate that unidirectional SBF may be useful in future explorations of perception of transparency, and of illusory form, in infancy (cf. Kellman & Shipley, 1991).

The results from infants' perception of contour in the illusory and dot displays suggest that other kinds of motion discrimination, in addition to SBF, specify shape from kinetic information. The illusory contour displays of Experiment 1, in particular, are similar in principle to stimuli used by Wattam-Bell (1991, 1996a, 1996b) to probe the emergence of motion sensitivity. He has reported that only after 6 to 8 weeks after birth do infants respond as if they detect differences in moving patterns in sparse random-dot displays, based on evidence from visual-evoked potentials and preferential-looking experiments. A recent report of neonates' discrimination of translating and rotating displays (Laplante, Orr, Neville, Vorkapich, & Sasso, 1996), however, casts some doubt on the conclusion that development of motion discrimination is an all-or-nothing phenomenon that emerges rather abruptly. The success of the present experiments with 2-month-olds suggests that this kind of dynamic random-dot display can play a central role in further investigations of the emergence of motion discrimination in younger age groups, by focusing on contour perception.

Finally, it is worth noting that the infants in all three experiments achieved a high level of performance, including the condition in which the outlines of the square and cross were not well defined (the dot shapes in Experiment 3), which implies that they may not have perceived crisp boundaries even in Experiments 1 and 2. Nevertheless, the kinetic illusory square and cross shapes were clearly evident to both the infants and the adults. Our experiments provide important clues into how such percepts can be attained so soon after birth, by showing sensitivity to and utilization of several kinds of motion information.

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