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Development of Three-Dimensional Form Perception

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In three experiments with infants and one with adults we explored the generality, limitations, and informational bases of early form perception. In the infant studies we used a habituation-of-looking-time procedure and the method of Kellman (1984), in which responses to three-dimensional (3-D) form were isolated by habituating 16-week-old subjects to a single object in two different axes of rotation in depth, and testing afterward for dishabituation to the same object and to a different object in a novel axis of rotation. In Experiment 1, continuous optical transformations given by moving 16-week-old observers around a stationary 3-D object specified 3-D form to infants. In Experiment 2 we found no evidence of 3-D form perception from multiple, stationary, binocular views of objects by 16- and 24-week-olds. Experiment 3A indicated that perspective transformations of the bounding contours of an object, apart from surface information, can specify form at 16 weeks. Experiment 3B provided a methodological check, showing that adult subjects could neither perceive 3-D forms from the static views of the objects in Experiment 3A nor match views of either object across different rotations by proximal stimulus similarities. The results identify continuous perspective transformations, given by object or observer movement, as the informational bases of early 3-D form perception. Detecting form in stationary views appears to be a later developmental acquisition.

The topic of form perception and its origins has occupied a central place in perceptual theory over the past 2½ centuries and in developmental research over the past 2½ decades. Most early research on the development of visual form perception used two-dimensional (2-D), pictorial, and often schematic stimuli (for reviews see Fantz, Fagan, & Miranda, 1975; Salapatek, 1975). This early research revealed infants' sensitivity to a range of sensory and pattern variables, and it also led to the refinement of a variety of methods for studying infant perception.

It has lately become more common for research in the development of visual perception to focus on three-dimensional (3-D) objects (Gibson, Owsley, Walker, & Megaw-Nyce, 1979; Kellman, 1984; Kellman & Spelke, 1983; Ruff, 1978). The reasons for this shift are several. In the first place, it is clear that the most behaviorally relevant form characteristics of objects are their 3-D forms, not particular 2-D patterns projected to particular vantage points. Second, an assumption often implicit in much pattern perception research was that study of the 2-D case would somehow lead to an understanding of 3-D perception. Such a view derives from a long-standing empiricist tradition in perception (Hebb, 1949; Mill, 1865/1965; Piaget, 1954). According to Mill, for example, an object consists of its "permanent possibilities of sensation"; the 3-D form of an object arises from, and consists of, the association of the various 2-D images it gives to an observer from different positions, orientations, and so forth.

Recent results in both adult and infant perception suggest something of a Copernican revolution in the way 2-D pattern perception and 3-D form perception are thought to be related. Ecological and mathematical analyses of information available for visual perception have suggested the superiority of information given over time, by motion of objects or observers, in specifying the 3-D forms of objects and the layout of space (Braunstein, 1976; Gibson, 1966, 1979; Johansson, 1970, 1975; Lee, 1974; Longuet-Higgins & Prazdny, 1980). Such information is often not definable in momentary views of scenes. A number of investigations of adult performance indicate persuasively that this kind of information can be used by perceivers (Braunstein, 1976; Johansson, 1975; Todd, 1982) and that it may outweigh or override conflicting information given in stationary viewing (Braunstein, 1976; Wallach & O'Connell, 1953). Several theorists (Gibson, 1979; Johannson, 1984) have gone so far as to suggest that perception of stationary arrays by stationary observers is a limiting or degenerate case of more fundamental perceptual processes dealing with changing stimulation.

The key element of claims that at least some perceptual abilities are based on information given over time is that the relevant information is not definable in any momentary view, but only across time. This is most obvious in cases where all momentary views consist of fields of apparently unstructured random dots, but when motion is added, structure is perceived (Braunstein, 1976). Closely accompanying claims about the nature of infor-

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mation have been suggestions that the use of such information depends upon perceptual mechanisms specialized for the pickup of change information (Gibson, 1966; Johansson, 1970).

Specialized mechanisms are suggested by the uniformity and rapidity of adult responses to motion information about 3-D structure (Johansson, 1975) and by the strict time constraints governing perception of structure from motion. Although rapidly sequenced stationary views (apparent motion) apparently tap into the motion and change detection systems as well as do continuous changes, sequential static views that do not evoke apparent motion will not reveal 3-D structure from change information (Braunstein, 1976; Johansson, 1975; Kellman & Cohen, 1984). The fact that any system for detecting continuous change can be triggered by multiple static views if they are dense enough in time and space has caused confusion in this domain. In our view, claims about mechanisms specialized for detecting change depend on two criteria: (a) The relevant information must require definition in terms of spatiotemporal relations, and (b) the system must repond to changes occurring only in a restricted spatiotemporal range. The clear contrast to such a system is one in which information available in momentary views is extracted and stored; comparisons of stored information, inferences about the relations of the views, and so on should not show confinement to particular spatiotemporal intervals (cf. Wertheimer, 1912). The impossibility of detecting 3-D structure from viewing a set of separate pictures taken from a random-dot cinematogram illustrates the argument for specialized change detection mechanisms.

Recent research suggests that mechanisms sensitive to temporally extended information may be fundamental in the development of 3-D form perception (Kellman, 1984, 1987; Owsley, 1983; Yonas, Arterberry, & Granrud, 1987). Infants use information in optical transformations to perceive objects and events in the 3-D environment before they appear capable of using information in static arrays.

In this article we report new findings about the generality, limitations, and informational bases of these early abilities. In Experiment 1, we report the first test of 3-D form perception from information given by motion of the observer, rather than motion of objects. In Experiment 2, we examine limitations in early form perception from static viewing by testing 16- and 24-week-olds with multiple static views of real objects. In Experiment 3, we seek to separate perspective transformations as information about 3-D form from surface information.

This set of experiments also provides convergent evidence on a number of methodological questions that have arisen in connection with previous research. Experiment 1, demonstrating 3-D form perception from motion of the observer, adds to the evidence that the structure of the information in continuous optical transformations, rather than some attentional effect of object motion, underlies early form perception. Experiment 2, suggesting that sequential static views of real objects do not indicate 3-D form to infants, bolsters earlier findings with the same objects in which the static views were rendered by photographic slides. Finally, Experiment 3 renders implausible the possibility that infants' patterns of responding previously interpreted as showing 3-D form perception might be explainable by subtle similarities among proximal stimuli.

Experiment 1

Evidence that infants perceive 3-D form from information in optical transformations has come exclusively from situations in which stationary observers viewed moving objects. For example, Kellman (1984) habituated infants to videotapes of a 3-D object (shown schematically in Figure 1) undergoing continuous rotation around two different axes on alternate habituation trials. After habituation, subjects were tested alternately with the same object rotating around a third, new axis and a different object rotating around the same, new axis. The use of different rotation axes allowed test of 3-D form perception with particular proximal stimuli that had not been seen previously. Infants generalized habituation to the same object in a new axis of rotation and dishabituated to the different object. Two control groups were habituated and tested in the same way, except that the displays contained sequential static views (photographic slides) taken from the rotation events. One group saw 6 views per cycle, spaced 60° apart, for 2 s each. The other group saw 24 views per cycle, spaced 15° apart, for 1 s each. The 0.5-s inter-view interval was too long to allow apparent motion between views. Neither control group responded differently to the two test sequences as a function of the 3-D object whose views had been seen in habituation.

The results were interpreted as showing that infants use information in continuous optical transformations to perceive 3-D form. From the results in the two static conditions, it appeared that infants at this age do not perceive 3-D form from single or multiple static views of objects as adults do. This conclusion must be qualified by the fact that the static views were presented as photographic slides, rather than real object views. Slides may have presented a cue-conflict situation, because information for a flat surface was present in addition to the information for 3-D form. The results in the static conditions also confirmed that kinetic group infants responded to 3-D form; infants did not discriminate between the objects on the basis of proximal stimulus similarities from a given object in different rotations. If they had, then the static groups should have shown a pattern similar to the kinetic group.

In Experiment 1, we sought to extend earlier findings to conditions in which the crucial information is given by movement of the observer (motion perspective). Projective geometry implies that optic flow information generated by an object rotating in depth can also be generated by movement of the observer around the object. If this information underlies early form perception, the forms of stationary objects should be perceivable if the observer is moved appropriately while viewing them. If, on the other hand, previous results depended not on the nature of the information available, but on attention-getting or other effects of moving objects, then form perception should not occur in this situation.

Method

Subjects. Twenty-four full-term infants, ranging in age from 110 to 126 days (M age = 118.5 days), served as subjects. They were recruited from the western suburbs of Philadelphia by letter and telephone, after being identified from newspaper birth announcements. An additional 14 subjects began the experiment but did not complete it—9 because

of fussing, 4 because of equipment failure, and 1 because of experimenter error.

Displays and apparatus. The two display objects used were the same as those used in a previous study (Kellman, 1984); they are pictured schematically in Figure 1. The objects were made of wood and were painted red. Both objects were 10-cm high, 5-cm wide and 5-cm deep at their greatest extents. At the infant's viewing distance of 54 cm, the objects subtended maximum visual angles of 10.6° (height) and 5.3° (width, depth). Objects were presented in different orientations on different trials by inserting a vertical metal rod (3-mm diameter) into three different holes in the objects. Objects were presented at eye level in a wooden display case, 66-cm high, 62-cm wide, and 41-cm deep. The display case was painted white. A sheet of white cardboard, 25-cm high, extended across the bottom part of the display case opening to conceal the stand supporting the object. A cardboard screen slid on a track to reveal or close off the displays at trial beginnings and ends.

The subject's chair was a standard infant chair that was moved by hand 50 cm back and forth along an arc around a point 30.5 cm away (see Figure 2). The chair was moved via a long handle extending from the side of the chair's base. The handle extended out past the curtains surrounding the seating area so that the person moving the chair would not be visible to the subject. The rate of movement was 10 cm/s, and the subject moved 45° around the display object, which was 54 cm away. After each movement of the subject in one direction, the object was occluded for 0.5 s by a card on a mechanical arm and rotated 60° around the vertical to a new position. The occluding card was made of white cardboard with rounded corners and measured about 18 cm × 21.5 cm. When it appeared, it was 5 cm in front of the object. The mechanical arm was operated by means of a cord extending beyond the display case. The occluding card and mechanical arm were hidden behind the cardboard sheet across the bottom of the front of the display case, except when the object was being occluded. Changing the object's position served to display all surfaces of an object at some time during a trial, inasmuch as the subject's movement was restricted to 45° around the object.

Movement of the subject around the stationary object placed upon a vertical axis in different ways provided projective geometric information similar to that given to a stationary viewer by a rotating object. The three rotation axes of the two objects used are illustrated in Figure 1.

Design and procedure. All of the infants were tested using a habituation-of-looking-time procedure. To isolate responding to 3-D form, the method of Kellman (1984) was used. Infants were habituated to a single 3-D object shown in two different axes of rotation on alternating habituation trials. After habituation, subjects were tested for looking time to the same object in a new axis of rotation and the new object in the same, new rotation. If the object's 3-D form was perceived, then habituation of looking time should have generalized to the same object in a new rotation. The new object should have evoked dishabituation. Two different rotation axes were used during habituation to avoid dishabituation based on the new axis of rotation during the test trials (Kellman, 1984).

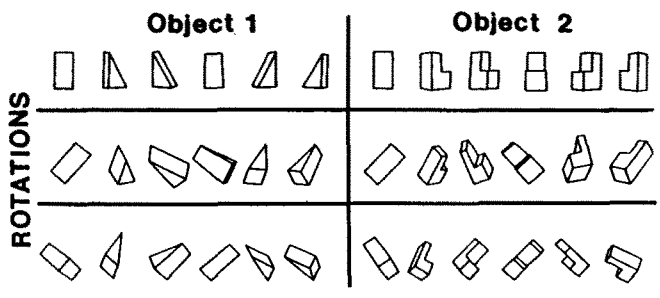

Figure 1. Schematic views of objects and rotation axes used in Experiment 1. (Successive views 60° apart are shown. All views in the same column are from the same 3-D object; views in the same row are from a single axis of rotation.)

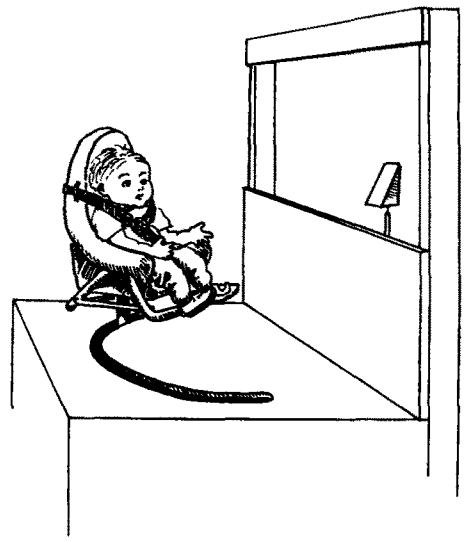

Figure 2. Motion perspective apparatus used in Experiment 1. (The observer was passively moved while viewing stationary objects. See text.)

To begin the experiment, a subject was seated in the infant seat, and side curtains were closed to eliminate any view of the room. Parents viewed the baby on a video monitor connected to a camera on top of the display case aimed through an opening at the subject. An experimenter began and ended each trial by sliding away or replacing the cardboard screen in front of the display case. An infant control habituation procedure was used. After an initial fixation of at least 0.5 s, a trial would continue until the infant looked away for 2 continuous seconds, up to a maximum of 120 s of looking time. The dependent variable on each trial was the total looking time accumulated. An intertrial interval of 6 s separated all of the trials in the experiment.

A single object was shown in two different rotations on alternate trials until the criterion of habituation was met. The criterion was a 50% decrease from a subject's initial looking levels, calculated over three trial blocks. If total looking time on the first three trials did not exceed 12 s, the habituation criterion was set by the first three consecutive trials that did exceed 12 s. Test trials consisted of alternating presentations of the old and new objects, three times each, in the same rotation. The test rotation was always different from the two rotations used in habituation.

Habituation object, rotations used in the habituation and test periods, and the order of test object presentation were completely counterbalanced.

Looking time was normally measured by two trained observers, using push-button inputs to a computer. In the cases of 4 subjects, only one observer was available. Observers viewed the infant through small holes at the upper corners of the back panel of the display case. Observers could not see the objects being presented. When two observers were present, interobserver agreement (proportion of the total time that both observers registered a look or nonlook) averaged .94, and ranged from .88 to .99. One observer was designated as the primary observer. His or her responses were used by the computer to determine the ends of individual trials and also the habituation period. The primary observer also decided whether to suspend or terminate the experiment if an infant became fussy. A third person changed the displays and opened and

closed the display screen as signaled by the computer. A fourth person moved the infant's chair.

Dependent measures and data analyses. The main dependent measure was dishabituation, defined as a subject's looking time on the first test trial presentation of each test display minus his or her looking time on the final trial of the habituation period. A preliminary analysis of variance (ANOVA) assessed the dishabituation data for main effects and interactions involving which object was shown first in the test period, which object was used in habituation, and which of the habituation rotations was shown first. There were two main analyses of the dishabituation data. First, a 2 × 2 ANOVA with habituation object as a between-subjects factor and test object as a within-subjects factor was carried out, followed by individual comparisons to determine the loci of significant overall effects. Tests of dishabituation levels against the hypothesis of zero dishabituation were also performed. Second, the number of subjects (out of 24) who showed greater recovery of looking time to the new object than to the old object on the first test exposure of each was compared with the null hypothesis (50%) by binomial test. Analyses of looking times over all three test trials, without correction for final habituation levels, were also carried out.

Results

Preliminary analyses. Preliminary analyses indicated no significant effects or interactions involving which object was shown first in the test trials and no effects of specific rotation axes.

Dishabituation analyses. Figure 3 shows looking times on the last six habituation trials and the test trials for the motion perspective group. Table 1 shows looking times on the final habituation trial and looking time on the first test exposure of each object by habituation object and test object. A two-way ANOVA with habituation object (1 and 2) as a between-subjects variable and test object (1 and 2) as a within-subjects variable was carried out on the dishabituation data (first test trial minus final habituation trial looking time). There was a reliable interaction of habituation object and test object, $F(1, 22) = 4.86$, $p < .05$, and no reliable main effects. Individual comparisons showed that infants who were habituated to Object 1 dishabituated reliably more to Object 2 than to Object 1, $t(11) = 2.05$, $p < .05$, one-tailed, whereas the numerically greater dishabituation to Object 1 by infants habituated to Object 2 did not reach significance, $t(11) = 1.52$, $.05 < p < .10$, one-tailed. In all, 18 of the 24 subjects looked longer at the new object than at the old object on the first test trial, $p < .01$, by binomial test.

Absolute dishabituation levels were assessed by comparing recovery scores to the old and new objects to 0. Recovery to the old object did not differ from 0, $t(23) = 0.22$, *ns*, whereas recovery to the new object was reliably greater than 0, $t(23) = 3.07$, $p < .01$.

Analyses of looking times over all three test trials, without correction for final habituation levels, supported the main findings above.

Discussion

The results of this experiment suggest that information given by motion of the observer can indicate the 3-D form of a stationary object to infants. Infants generalized habituation to the same object in a new axis of rotation and dishabituated to a new object. This outcome was likely based on detection of 3-D form, rather than on similarities in the proximal stimuli from the same object in different rotation axes. In previous research using sequential static views (photographic slides) of the same objects, infants did not show any discrimination between test objects as a function of habituation condition (Kellman, 1984). Moreover, those same results suggested that information in continuous transformations given by relative motion between the object and the observer specified 3-D form.

In the present study, however, this conclusion is tentative. The previous research used 2-D projections of objects, both in the continuous transformation condition (videotape) and in the two static conditions (slides). In both of those situations, conflicting information about the flatness of the viewing screen may have been available. Although any such cue conflict did not prevent 3-D form perception in the kinetic group, it may nevertheless have affected the outcomes of the static conditions. In the present study, using real objects, infants may have detected 3-D form from single or multiple static views. Experiment 2 was designed to test the possibility that infants perceive 3-D form from information in stationary arrays.

Experiment 2

Adults can usually perceive 3-D form from single views of an object. Early studies (Cook, Field, & Griffiths, 1978; Ruff, 1978) failed to find evidence of 3-D form perception from multiple stationary views of objects even at 6 months of age, although in Ruff's studies the objects were rather complex. Other studies suggest that even with simpler displays, infants do not perceive 3-D form from single or multiple static views of objects, at least not at 4 months of age (Kellman, 1984; Owsley, 1983). In Owsley's (1983) experiment, 3-D form was not perceived from multiple monocular views of part of an object. However, the same study suggested that stereoscopic viewing of an object by 16-week-olds could allow recognition of part of an object previously indicated by motion information.

Recently, Yonas et al. (1987) reported transfer from kinetic depth information about form to stereoscopic information at 4 months of age, but only for infants who showed disparity sensitivity in a pretest. Twenty-five of their 73 four-month-old subjects passed the pretest, which consisted of a visual preference test between two displays of vertical black and white bars. Two bars in one of the displays projected disparate images to the two eyes (30-min uncrossed disparity), making that display appear 3-D to observers with stereoscopic depth perception. Infants who did not pass the pretest did not, as a group, discriminate between the previously viewed object and a different 3-D object.

Given these findings, it is unclear whether infants in Experiment 1 of the present work must have perceived form from information in continuous perspective transformations. It is possible that information in single or multiple static views of the objects could have allowed perception of form, at least for some infants at this age.

To test this possibility, we presented multiple stationary views of the objects used in Experiment 1 to groups of infants at 4 and 6 months of age. If infants perceived 3-D form from information available in static viewing, then we expected infants who were habituated to views of one object to generalize habituation to that same object in a new axis of rotation and to dishabituate

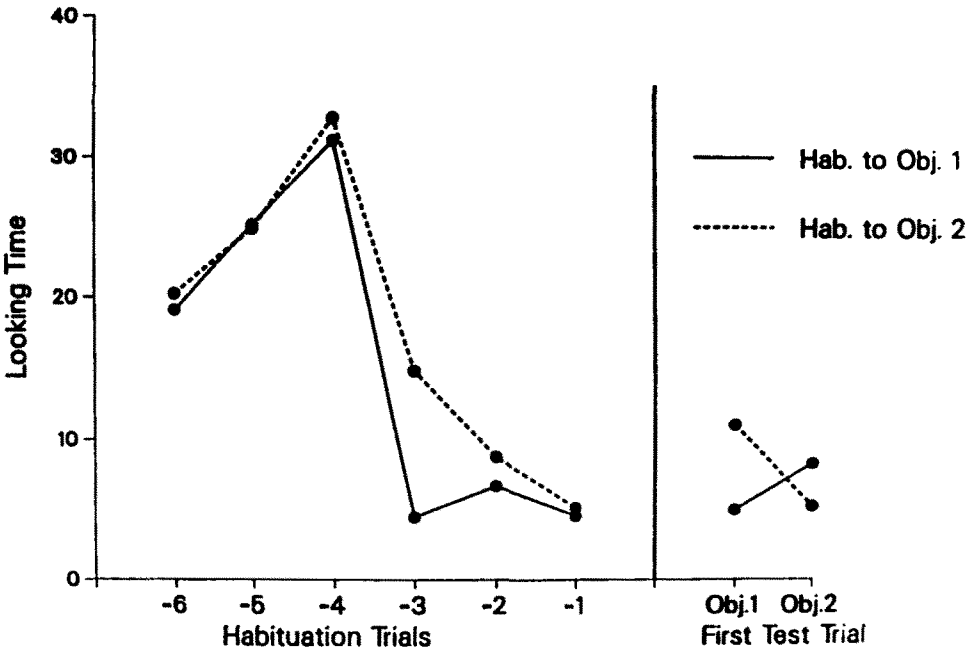

Figure 3. Looking times during habituation and test trials in Experiment 1. (Habituation trials are numbered backward from the trial on which the habituation criterion was met. Separate curves are shown for infants who habituated to each object.)

to a different object. Six-month-old infants were tested because by that age the onset of stereopsis has occurred for almost all infants (Birch, Gwiazda, & Held, 1982). Because 16 weeks is a transitional period for the onset of stereopsis, results at that age might be obscured by the differences within the group.

Method

All details of method in Experiment 2 were the same as in Experiment 1, except as noted.

Subjects. Subjects were 48 full-term infants. The 4-month-old group ranged in age from 100 days to 128 days (*M* age = 116.5 days). The 6-month-old group ranged in age from 151 days to 200 days (*M* age = 174.8 days). An additional 51 subjects began the experiment but did not complete it—44 because of fussing, 4 because of equipment failure, and 3 because of experimenter error. Failure to complete the experiment because of fussing was unevenly divided between the groups; it occurred 10 times in the younger group and 34 times in the older group.

Table 1
Looking Time by Habituation Object and Test Object in Experiment 1

Habituation object	Looking time (in seconds)		
	Final habituation trial	Test object	
		Object 1	Object 2
Object 1	4.6	5.0	8.3
Object 2	5.2	11.1	5.3

Displays and apparatus. The two objects used were the same as in Experiment 1. They were displayed atop a swiveling stand with a circular Plexiglas base to allow precise control of their positions. The stand fit onto a larger stationary base. A small roller on a metal arm that was attached to the stationary base was spring-loaded against the rim of the Plexiglas base so as to be able to snap into notches cut every 15° around the rim.

Display presentation throughout the experiment consisted of 1.5-s exposures of the object followed by 0.5 s of occlusion by the card on the mechanical arm, during which the object was rotated 15° (counterclockwise from above) around the vertical axis. The object was then revealed for 1.5 s again, and so on. As in Experiment 1, three different axes of rotation were obtained by attaching the vertical rod to three different points on the object. The axes of rotation were identical to those in Experiment 1; for each rotation, infants viewed sequences of 24 static views spaced 15° apart.

Design. As in Experiment 1, infants were habituated to a single 3-D object shown in two axes of rotation on alternate habituation trials. After habituation, they were tested for dishabituation to the same object in a new rotation and a new object in the same, new rotation.

Procedure. All aspects of procedure were the same as in Experiment 1, except for display presentation as previously described. Observer agreement ranged from .78 to .98 and averaged .90. Two observers were available for all but 6 subjects.

Results

Preliminary analyses. There were no reliable main effects or interactions involving test object order or rotation axes used in habituation.

Dishabituation analyses. Figures 4 and 5 display looking times during the habituation and test periods in the 16-week-old and 24-week-old groups, respectively. Table 2 shows looking

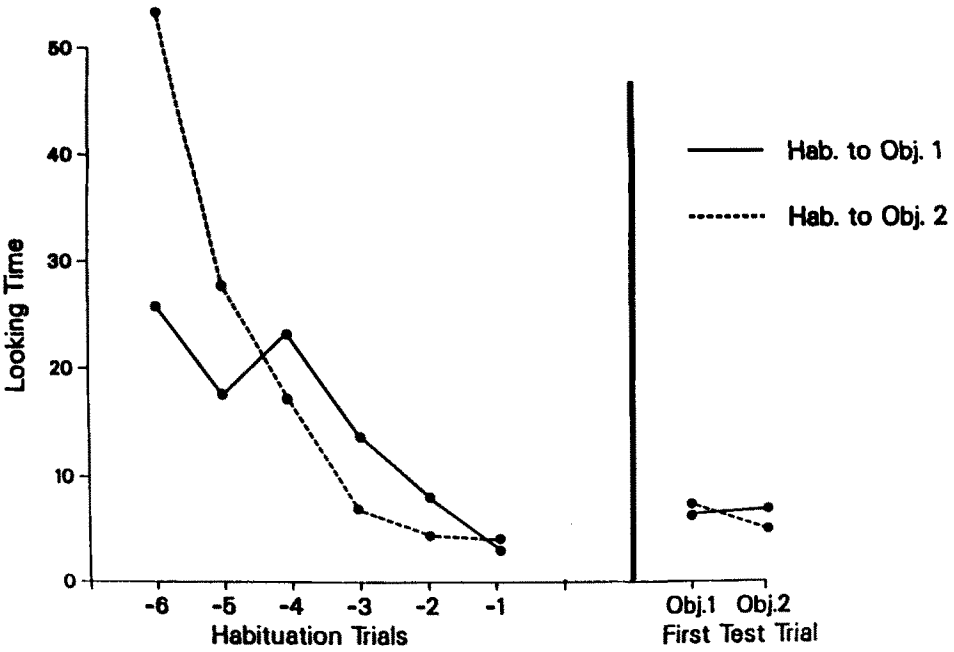

Figure 4. Looking times during habituation and test trials in Experiment 2 for 16-week-old group. (Separate curves are shown for infants who habituated to each object.)

time on the final habituation trial and on the first test trial exposure of each object. There appears to be no differential response to the two test objects as a function of habituation object. This pattern was confirmed by a 2 × 2 × 2 ANOVA, with age and habituation object as between-subjects variables and test object as a within-subject variable. There were no significant main effects or interactions, all $Fs < 1.73$, *ns*. ($F[1, 44] = 1.30$, *ns*, for interaction of habituation object and test object.) Fourteen of the 24 subjects in both the 16-week-old group and the 24-week-old group looked longer at the new object than at the previously exposed object on the first test trial with each, *ns* by binomial test.

Discussion

The results of Experiment 2 suggest that neither 16-week-old nor 24-week-old infants detected the 3-D forms of objects from information in single or multiple static views of these objects. After exposure to one 3-D object throughout the habituation period, there was no differential responding to the same object and a new object.

The results contrast starkly with adult performance under similar conditions. Adults detect the 3-D forms of these objects from virtually any of the static views shown in isolation. One possibility consistent with the present results is that the ability to perceive 3-D form in the absence of continuous transformations develops later. Perhaps it begins around the time that pictorial depth cues appear to become effective (Yonas, Cleaves, & Pettersen, 1978).

Conclusions about infants' inability to perceive form from static information should be regarded as somewhat tentative because such inferences stem from the absence of differences in responding based on previous exposure to a form. Nevertheless, the present results indicate that 3-D form is not an obvious or salient property of objects viewed in unchanging arrays at this age. Infants' attention to these displays was ample. As can be seen by examining Figures 4 and 5, looking times during the habituation and test periods were comparable in Experiment 2 to those in Experiment 1, in which infants showed evidence of form perception. Moreover, at looking times of this order or lower, infants of these ages have been shown to detect and discriminate a variety of aspects of displays including 2-D pattern, color, and orientation (see Cohen, DeLoache, & Strauss, 1979, for a review).

It remains possible that even if general attention was adequate, the frequent interruption of the stationary displays by the occluding card in Experiment 2 was distracting to infants. However, the occluding card also appeared once every 5 s in the motion perspective condition (Experiment 1). Moreover, different techniques for separating different views have been used in the various experiments that have failed to find 3-D form perception from static viewing. For example, Ruff (1978) showed different views on different trials, and Kellman (1984) separated views on a projection screen by brief intervals of darkness. In that study as well, analyses suggested that the differences between the kinetic and static groups were not explainable by looking-time differences. The weight of the evidence suggests that in static viewing, 3-D form perception is either not possible or not a natural mode of perceiving at these ages.

How does this assessment fit with reports of form recognition from stereoscopic information (Owsley, 1983; Yonas et al., 1987)? On the surface, these two lines of evidence seem to con-

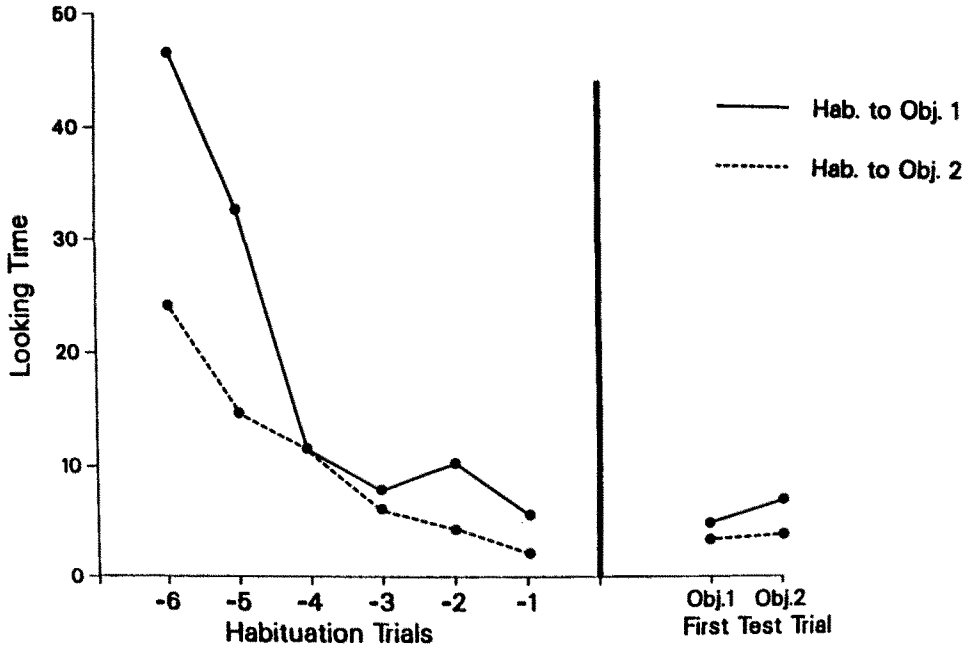

Figure 5. Looking times during habituation and test trials in Experiment 2 for 24-week-old group. (Separate curves are shown for infants who habituated to each object.)

flict, especially for the 24-week-old group in the present study. It could be argued that the present procedure is difficult for infants because the object's position is changed while it is shielded from view. However, if an object's form can be perceived stereoscopically from each stationary presentation, it is hard to understand why changing position (especially by increments as small as 15°) should cause a problem.

A possible resolution of the apparent discrepancy among these findings is that stereoscopic information may be used more easily to recognize a form previously specified by motion information than to perceive form initially. If only some 3-D features, but not whole form, can be gleaned from static viewing, these may still be adequate for habituation to generalize. In both the Owsley (1983) and the Yonas et al., (1987) experiments, stereoscopic presentation was used only after exposure of a form from kinetic information. Reversing the direction of such transfer experiments would be an interesting future study.

The difference between the outcomes in Experiments 1 and 2 seems to be the availability of information in continuous optical transformations. Identical objects in identical orientations were used in the two studies, with the only difference being the mode of presentation. Taken together, the results of Experiments 1 and 2 suggest that early capacities to perceive form depend on the nature of the information available. Information in continuous optical transformations seems to indicate whole form, whether those transformations are generated by motion of an object or of the observer.

To our knowledge, Experiment 1 provides the first evidence of young infants' initial detection of the 3-D forms of ordinary, stationary objects, although, as has been discussed, other work has suggested that form perceived from optical transformations can be recognized stereoscopically. From a developmental standpoint, the ability of infants to detect form when moved passively through environments may well be more important to early learning than observation of the comparatively few objects that rotate relative to the observer.

Table 2
Looking Time by Group, Habituation Object, and Test Object in Experiment 2

Group and habituation object	Looking time (in seconds)		
	Final habituation trial	Test object	
		Object 1	Object 2
Static (4 months)			
Object 1	3.4	7.0	7.5
Object 2	4.8	7.9	5.8
Static (6 months)			
Object 1	6.0	5.1	7.6
Object 2	2.6	4.0	4.5

Experiment 3A

Our studies of the origins of 3-D form perception have so far left unspecified the exact nature of the information provided by continuously transforming optical information. Mathematical analyses of motion information have emphasized perspective transformations, changes in the contours and surfaces of an object resulting from changing distance, and orientation relative to the observer. The changing projection of a 3-D object also ordinarily contains changes in brightness and texture gradients,

which may also give form information (Crowell, 1986; Todd, 1985).

Shaw and Bushnell (1983) suggested that changes in brightness and texture are necessary for early 3-D form perception. Using a shadow-casting technique, they displayed perspective tranformations of a rotating object in the absence of brightness and texture gradients. They reported that 24-week-olds generalized habituation from such a display to presentation of the real object but that 16-week-olds did not. Taken together with the results of Kellman (1984), these results can be interpreted to suggest that brightness and texture information, which was present in Kellman (1984), is required for 16-week-olds to perceive form.

Other explanations are possible, however. For one, the use of shadow casting with solid objects eliminated perspective information from internal contours of objects (contours that fall within the projection). It is unclear whether young infants should perceive 3-D form under such circumstances; moreover, the apparent success of 24-week-olds may have been due to superior ability to detect proximal stimulus similarities, rather than equivalent form, in the habituation and test displays.

In Experiment 3, we tested whether continuous perspective transformations of an object's bounding contours, in the absence of surface texture and shading information, could serve as information for form perception by 16-week-olds. Perspective transformations without surface information were presented by using videotapes of wire figures similar to those used by Wallach and O'Connell (1953) in the original "kinetic depth effect" studies.

A secondary purpose of this experiment was to perform an additional check on the inferences of previous work. The method of Kellman (1984), used in all of the studies in this series, isolates responses to 3-D form by changing the proximal stimuli on which form perception can be based. To the extent that the 2-D views of the same object in different axes of rotation resemble each other, appropriate patterns of dishabituation could arise without implying that infants perceive 3-D form.

Some contortions are required to describe the 2-D views from a single object in Kellman's (1984) study or the present Experiments 1 and 2 in such a way as to predict generalization of habituation across axes of rotation based on 2-D pattern perception. The objects were designed so that line lengths, orientations, angles, surface areas, brightness relations, and so forth in the 2-D patterns underwent drastic changes for a single object across different rotation axes and maintained many similarities between the two different objects when in the same rotation. Empirically, the 2-D patterns did not support discrimination of the old and new objects, as shown by tests with the static views.

The present study, however, incorporated an even stronger test. We used objects that (a) further minimized the discriminability of proximal stimuli between the two objects and (b) eliminated the possibility of 3-D form discrimination from static views. The latter manipulation allowed us to verify that adults could not accurately sort sequences of 2-D views from the two objects on the basis of similarity (Experiment 3B). Both of the 3-D objects were "parallelogram" figures, in the terminology of Wallach and O'Connell (1953): They both consisted of two triangles sharing a side (see Figure 6). The main virtue of this kind of figure lies in its composition from triangles. A theorem of projective geometry states that all triangles are projectively equivalent; that is, a 2-D triangular pattern could be the (polar) projection of any triangle whatsoever, in some appropriate position and orientation in 3-D space (Gans, 1969). In our study, we used two double triangle figures of the same overall height and width. They differed only in the angle at which the two triangles intersected, 95° in one case and 165° in the other case.

The displays were designed to minimize the information about 3-D structure available in static viewing; moreover, using two displays differing in only one respect maximized the similarities between views of the two different objects when they were in the same axis of rotation.

Axes of rotation were selected so that the particular optical transformations that revealed the relation of the two triangles differed in each case. For example, in one axis of rotation, both figures project momentarily as two lines intersecting. The angle of intersection differs for the 95° and the 165° figures. However, these particular views in this rotation constitute the only time at which the figures project to only two lines. As can be seen from Figure 6, in the other orientations the relations of the triangles making up each object are revealed in different ways.

Method

Subjects. Subjects were 48 full-term infants ranging in age from 106 days to 149 days (M age = 123.7 days). An additional 49 subjects began the experiment but did not complete it—45 because of fussing, 2 because of equipment failure, and 2 because of experimenter error.

Displays and apparatus. Two 3-D wire figures were constructed from 2-mm diameter wire. Both consisted of two triangles sharing a base. The objects had the same overall length and width, but differed in the angle of intersection of the two triangles. For one object this angle was 95°, whereas in the other it was 165°. Objects were presented by videotape on a 66-cm (diagonal) monitor. The objects' contours appeared as bright white lines on a dark field; on the monitor screen the objects extended at their greatest extent 28 cm (height) × 13 cm (width). At the infants' viewing distance (61 cm) the objects subtended visual angles of 26° (height) and 12.2° (width). In the kinetic group, objects were shown on videotape continuously rotating, making one complete revolution every 15 s. In the static group, multiple static views taken from the rotation sequences were shown on videotape. For each rotation type there were 24 views 15° apart, shown for 1.5-s durations and separated by a 0.5-s blank interval. Rotation was always around a vertical axis, but three different rotation types were obtained by attaching the objects in different ways to the axis. The objects and rotations used are pictured in Figure 6.

Design and procedure. The design and procedure were the same as in previous studies, except that trials begin by starting the videotape and then sliding away the cardboard screen. The intertrial interval was 8 s, which allowed time for changing of the videotapes. Observer agreement ranged from .80 to .97 and averaged .90. A second observer was unavailable for 10 subjects.

Results

Figure 7 shows the looking times during the habituation and test periods in the kinetic group, and Figure 8 shows them for the static group. Table 3 gives the looking time for each group on the last habituation trial and first test trial with each test object. Kinetic group infants appeared to dishabituate markedly to the novel object and seemed to generalize habituation

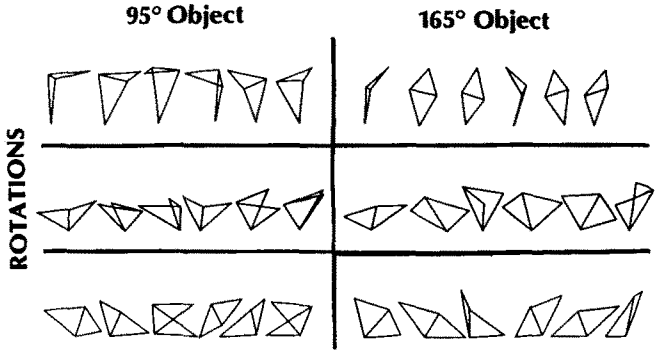

Figure 6. Views and objects and rotations used in Experiment 3. (Successive views 60° apart are shown.)

to the familiar object, whereas static group infants showed no differential response to the objects in the test trials as a function of habituation object. These patterns were verified by a 2 × 2 × 2 ANOVA. There was a reliable main effect of group, $F(1, 44) = 9.20$, $p < .01$, indicating greater total dishabituation in the kinetic group. There were reliable interactions of habituation object and test object, $F(1, 44) = 5.43$, $p < .025$, and of group, habituation object, and test object, $F(1, 44) = 7.05$, $p < .025$. Subsequent comparisons indicated that both interactions were due to differences in the kinetic group in dishabituation to the two test objects as a function of habituation object. Kinetic group infants who were habituated to the 165° object dishabituated reliably more to the 95° object, $t(11) = 2.11$, one-tailed, whereas the numerically greater dishabituation to the 165° object by infants who were habituated to the 95° object fell short of significance, $t(11) = 1.53$, $.05 < p < .10$, one-tailed. Static group infants showed no reliable differences in dishabituation to the two test objects as a function of habituation object, $t(11) = 0.12$, *ns*, for subjects who were habituated to the 95° object and $t(11) = 0.59$, *ns*, for subjects who were habituated to the 165° object. Sixteen of the 24 subjects in the kinetic group looked longer at the novel object on the first test trial, $.05 < p < .10$, by binomial test. In the static group, 10 of the subjects looked longer at the novel object on the first test trial, *ns*.

Levels of dishabituation to the old and new objects were tested against the hypothesis of 0 dishabituation in both groups. In the kinetic group, there was some dishabituation to the old object, $t(23) = 2.19$, $p < .05$, and substantial dishabituation to the new object, $t(23) = 3.90$, $p < .001$. In the static condition, there was some dishabituation to the old object, $t(23) = 1.88$, $p < .05$, one-tailed, and no reliable dishabituation to the new object, $t(23) = 0.68$, *ns*.

Experiment 3B

Informal study indicated that adults viewing the continuously transforming projections of the rotating objects on videotape uniformly perceived the true 3-D structure of the two objects. There was no difficulty in identifying the same object across different axes of rotation when continuous motion was used. It appeared that the ease of object perception by adults from the videotapes of rotation depended on continuous transformations rather than on any information available in momentary views. The present study was conducted to check this supposition by assessing both the information available about 3-D form in the 2-D views and the 2-D similarities within and between sets of views.

Method

Subjects. Subjects were 12 Swarthmore College undergraduates.

Displays and apparatus. Thirty-six static views of the two wire objects were traced from the video screen onto white paper with 1-mm thick black lines. Six views of each object, spaced 60° apart, along each of three rotations were used. These views are displayed in Figure 6.

Design and procedure. Subjects were tested in a procedure that paralleled the infant's exposure to the experimental displays. In the familiarization phase, a subject was handed a stack of 12 displays consisting of views of a single object in two axes of rotation. The 6 views from each rotation were stacked in sequence, and the two different rotations were not intermingled. The following instructions were read to the subject:

> This is an experiment on similarity and relatedness of various drawings. In the stack of drawings I have given you, all of the drawings are "1"s, or examples of Category 1. Your task is to look through them and become familiar with Category 1. When you are ready, I will give you some new drawings and you will be asked to sort each of them as to whether it is also a "1" (that is, it belongs in Category 1) or whether it is not a "1" (that is, it does not belong in Category 1).

After familiarization, the experimenter collected the first stack and presented the subject with another stack of 12 views. This stack consisted of 6 views of the same object whose views were shown previously and 6 views of the different object, both in a third, new rotation axis.

Subjects were scored as to how many of the 12 views they correctly sorted as being in Category 1; that is, each view sorted as a *1* that was a view of the same object shown in familiarization was scored as correct, whereas each view of the other object sorted as a *not 1* was scored as correct. The object whose views were shown in familiarization and the rotations used in familiarization and test were counterbalanced. Order of rotations used in familiarization and which object's views were on top of the test stack were randomized.

Results

All of the subjects seemed to understand the task and to deliberate carefully in the initial familiarization period and in sorting. When questioned after sorting, all of the subjects mentioned similarity criteria as the basis for their sorts. Four subjects said that membership in Category 1 encompassed all and only views of a single 3-D object; the sorts of these subjects were not superior to the group average.

Subject's sorting of views of the two test objects did not differ from chance. That is, subjects were as likely to classify 2-D views of the different object together with the views seen previously as they were to correctly classify views of the same object. The mean number of correct responses (out of 12 possible) was 6.4, which did not differ from chance, $t(11) = 0.71$, *ns*. The mean number of false alarms—views of the new object sorted as belonging to the initial category—was 3.5, and no subject had fewer than 2 false alarms. The mean number of hits—correct sortings of views of the old object—was 3.9; hits and false alarms did not differ statistically, $t(11) = 0.81$, *ns*.

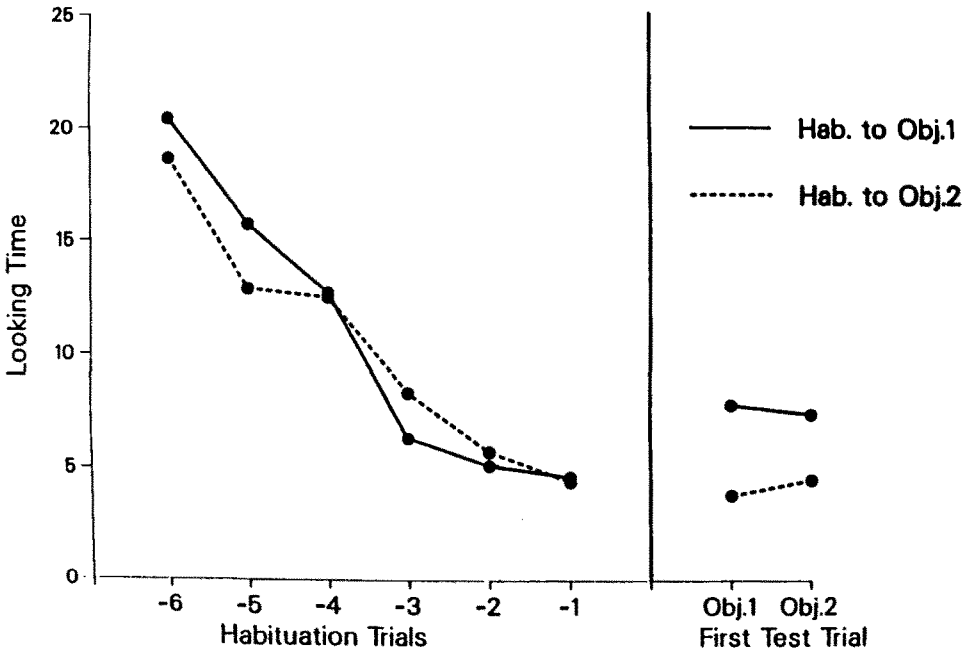

Figure 8. Looking times during habituation and test trials in Experiment 3B for static group. (Separate curves are shown for infants who habituated to each group.)

The findings of Experiments 3A and 3B indicate that 16-week-old infants perceive 3-D form from perspective transformations even in the absence of information from textural or shading transformations. The experiments do not rule out the possibility that transformations of shading and texture may also be informative, but they do show that perspective transformations can function in isolation.

In addition, Experiment 3A suggests that a restricted range of spatiotemporal continuity is required for form perception. Infants did not perceive form from static views spaced as closely as 15° and separated in time by 0.5 s. Such results are consistent with analyses of optical change information as being basic in 3-D perception (Gibson, 1966, 1979; Johansson, 1970). The form-perception abilities apparent in these studies may be based on perceptual mechanisms sensitive to information in optical transformations.

Table 3
Looking Time by Group, Habituation Object, and Test Object in Experiment 3

Group and habituation object	Looking time (in seconds)		
	Final habituation trial	Test object	
		Object 1	Object 2
Wire figures—static			
Object 1	4.6	7.8	7.4
Object 2	4.4	3.7	4.5
Wire figures—kinetic			
Object 1	11.8	14.5	23.4
Object 2	10.0	23.6	14.3

General Discussion

The present results extend and clarify our knowledge of early form perception. Infants by 16 weeks of age readily detect the 3-D forms of objects from information in continuous optical transformations. This information can be given by relative motions that include a component of rotation in depth of the object relative to the observer, regardless of which actually moves. Specifically informative in continuous optical changes are perspective transformations of the bounding contours of objects.

These findings meet stringent criteria for claiming that infants' responses to motion-carried information were based on perception of 3-D form and that the necessary information for form perception resides in continuous change. Previous research included static control groups that did not discriminate the objects used, either from proximal stimulus similarities across rotations or by detecting 3-D form from static information. Moreover, analyses of looking times by individuals and subgroups in the kinetic and static conditions in earlier work argued against explanations of group differences in terms of attention, at least insofar as attention could be assessed from looking time (Kellman, 1984). The present experiments rule out more exotic explanations in terms of proximal stimulus similarities and attention. Sixteen-week-old infants perceive 3-D form from continuous optical transformations even in cases in which the 3-D forms of the objects are ambiguous to adults in static viewing and those in which there is no greater similarity among views of the same object in different orientations than between views of different objects.

These results have significance for theories of the development of form perception. Three-dimensional form does not seem to be a summation of various possible 2-D views, as has

often been suggested. In fact, it is the relating of multiple static views of an object to some single, 3-D form that seems to present difficulties for young infants. Accumulating evidence about the origins of human form perception is more consistent with the suggestion that perceptual mechanisms sensitive to perspective change have developed over evolutionary time (Gibson, 1966, 1979; Johansson, 1970; Shepard, 1984). In these views, the projective geometric relations between objects and observers in relative motion derive from basic physical and ecological facts about 3-D space and light that have furnished an invariant basis for the evolution of visual perception.

The existence of form perception from optical transformations at 16 weeks of age does not rule out some contribution of learning to visual perception of 3-D form. As has been argued previously (Kellman, 1984), however, it is not clear what sort of learning theories remain plausible in the face of such findings. Infants at this age are not in general capable of self-locomotion or skilled manipulation of objects; thus, 3-D form perception seems unlikely to arise from simultaneous viewing and manipulating of objects, as most learning theories of object perception have suggested (Berkeley, 1709/1963; Piaget, 1954, 1977; Venger, 1977). Moreover, our findings and those of others that infants do not perceive 3-D form from single or multiple static views sharply constrain purely visual possibilities for learning. The problem is this: Suppose continuous optical transformations are not initially indicative of 3-D form, and learning makes them informative. Then, the information in optical change must become meaningful in connection with some other knowledge that infants have about 3-D form. In the world of the 16-week-old, static viewing does not seem to provide this knowledge, and the ability to make relatively precise visual–tactile connections lies some weeks in the future. Thus, available evidence points toward an innate substrate in this domain of perceptual knowledge.

The performance of infants seems to meet both criteria mentioned earlier for making inferences about mechanisms adapted to changing stimulation. The relevant information underlying early form perception seems to be definable only in terms of spatiotemporal relations. In addition, the processes by which infants at this age perceive 3-D form do not seem to operate if temporal and spatial gaps are introduced; that is, the relevant mechanisms seem to require spatiotemporal continuity or some close approximation. Our data suggest that the search for neurophysiological mechanisms underlying these abilities may prove to be fruitful (cf. Braddick & Atkinson, 1987).

The origins of adult abilities to detect overall form from stationary viewing remain obscure. Current evidence suggests that if these abilities exist at all in the first 6 months of life, they are tied to the onset of stereoscopic depth perception. Even that capacity, however, may not allow initial formation of a representation of 3-D form until later than 24 weeks. Whether form perception based on stereoscopic information or rules about object regularities arise from maturation or depend on inferences gleaned from experiences with objects awaits further investigation.

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The Publications and Communications Board has opened nominations for the editorship of the *Journal of Experimental Psychology: General* for the years 1990–1995. Sam Glucksberg is the incumbent editor. Candidates must be members of APA and should be available to start receiving manuscripts in early 1989 to prepare for issues published in 1990. Please note that the P & C Board encourages more participation by women and ethnic minority men and women in the publication process, and would particularly welcome such nominees. To nominate candidates, prepare a statement of one page or less in support of each candidate. Submit nominations no later than February 1, 1988, to

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