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Principles of Object Perception

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Research on human infants has begun to shed light on early-developing processes for segmenting perceptual arrays into objects. Infants appear to perceive objects by analyzing three-dimensional surface arrangements and motions. Their perception does not accord with a general tendency to maximize figural goodness or to attend to nonaccidental geometric relations in visual arrays. Object perception does accord with principles governing the motions of material bodies: Infants divide perceptual arrays into units that move as connected wholes, that move separately from one another, that tend to maintain their size and shape over motion, and that tend to act upon each other only on contact. These findings suggest that a general representation of object unity and boundaries is interposed between representations of surfaces and representations of objects of familiar kinds. The processes that construct this representation may be related to processes of physical reasoning.

This article is animated by two proposals about perception and perceptual development. One proposal is substantive: In situations where perception develops through experience, but without instruction or deliberate reflection, development tends to enrich perceptual abilities but not to change them fundamentally. The second proposal is methodological: In the above situations, studies of the origins and early development of perception can shed light on perception in its mature state. These proposals will arise from a discussion of the early development of one perceptual ability: the ability to organize arrays of surfaces into unitary, bounded, and persisting objects.

PERCEIVING OBJECTS

In recent years, my colleagues and I have been studying young infants' perception of objects in complex displays in which objects are adjacent to other objects, objects are partly hidden behind other objects, or objects move fully

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out of view. We have focused on object perception in cluttered, changing arrays for three reasons. First, cluttered arrays are the norm in ordinary environments: Objects rarely stand against a homogeneous medium, separated from one another and continuously, fully in view. More commonly, objects sit upon and beside other objects, they are partly hidden by objects closer to the viewer, and they enter and leave the visual field sporadically as the viewer, or some object, moves. No mechanism for segmenting the surface layout into objects could operate effectively if it could not determine the boundaries between objects that are adjacent, the complete shapes of objects that are partly occluded, and the persisting identity of objects that move out of sight.

Second, apprehending objects in a rich and changing environment is necessarily a process of going beyond the immediately visible surface layout to capture the underlying arrangement of bodies that gave rise to that layout. This accomplishment can be viewed as a kind of perceptual inference (Helmholtz, 1925; Hochberg, 1978). So viewed, it may shed light on basic principles and assumptions that govern object perception in any situation.

Third, the ability to organize unexpected, cluttered, and changing arrays into objects is mysterious: so mysterious that no existing mechanical vision system can accomplish this task in any general manner. It has been suggested that this task is impossible in principle: One cannot perceive the unity, boundaries, and persistence of objects in general, but only the unity, boundaries, and persistence of objects of particular kinds (Hume, 1962; Wiggins, 1980; see also Marr, 1982). Thus, there is no separate stage of object segmentation in a number of current object recognition procedures, which both categorize objects and find their boundaries by fitting models of familiar objects to unsegmented representations of visual arrays (e.g., Huttenlocher, 1988).

Contrary to this view, I will suggest that general segmentation processes serve to divide visual arrays into objects. These processes permit inexperienced perceivers to apprehend physical objects as persisting bodies with internal unity and stable boundaries. The same processes also might facilitate object recognition by experienced perceivers, because they constrain the portions of a visual array to which models of particular kinds of objects can be matched. Studies of infant perception may be especially well placed to shed light on these processes, however, because infants lack models for most categories of objects. In infancy, processes for segmenting arrays into objects are not overlaid and obscured by processes for recognizing objects of a multitude of kinds.

Our research suggests that the processes by which humans apprehend objects occur relatively late in visual analysis, after the recovery of information for three-dimensional surface arrangements and motions. The processes appear to accord with four principles—*cohesion, boundedness, rigidity,* and *no action at a distance*—that reflect basic constraints on the motions of physical bodies. These principles may be central both to human perception of objects and to human reasoning about object motion.

The present, brief overview is divided into four parts. First, I discuss the principal negative finding from experiments on object perception in infancy: Infants do not appear to perceive objects by virtue of any general tendency to confer the simplest, most regular organization on visual experience. Second, I outline the principal positive findings of these experiments: Young infants perceive objects as unitary, bounded, and persisting bodies by analyzing surface arrangements and motions. Third, I propose a partial account of these findings in terms of the four principles of object motion. Finally, I speculate on the implications of these findings for theories of object perception by adults (and for artificial vision systems) by considering the ways in which perception might and might not change with the growth of knowledge.

GESTALT RELATIONS AND OBJECT PERCEPTION IN INFANCY

My search for the principles of object perception began with two traditional proposals: The Gestalt psychologists' effort to understand object perception in terms of the principle of "Prägnanz," and the empiricist effort to understand object perception in terms of principles of sensation and association.

According to Gestalt theory, perception tends inherently to assume the simplest and most regular organization that is consistent with a given visual array (Koffka, 1935; Köhler, 1929; Wertheimer, 1958; see also Hatfield & Epstein, 1985). This tendency underlies the organization of visible surfaces into objects. For example, a partly occluded object will appear to continue behind an occluding surface whenever such a continuation produces units that are more homogeneous in color and texture (principle of similarity), more smoothly contoured (principle of good continuation), more regular in shape (principle of good form), and more uniform in their motion (principle of common fate), than the fragments of surfaces that are directly visible.

According to empiricist theories, in contrast, perception initially corresponds only to that which is immediately given to the senses (e.g., Berkeley, 1910; Helmholtz, 1925). Perceivers learn to go beyond immediate sensory patterns by acting on the world, relating their changing visual sensations to each other and to sensations arising from their actions. On this view, infants first perceive only the visible fragments of an array. As infants manipulate the surface layout and move around it, they come to learn that certain properties of visual arrays are related to certain properties of the bodies they feel. For example, children may learn that collinear edges in a retinal array tend to lie on a single displaceable body (Helmholtz, 1925; Brunswik & Kamiya, 1953). In this way, perception comes to accord with the principle of good continuation.

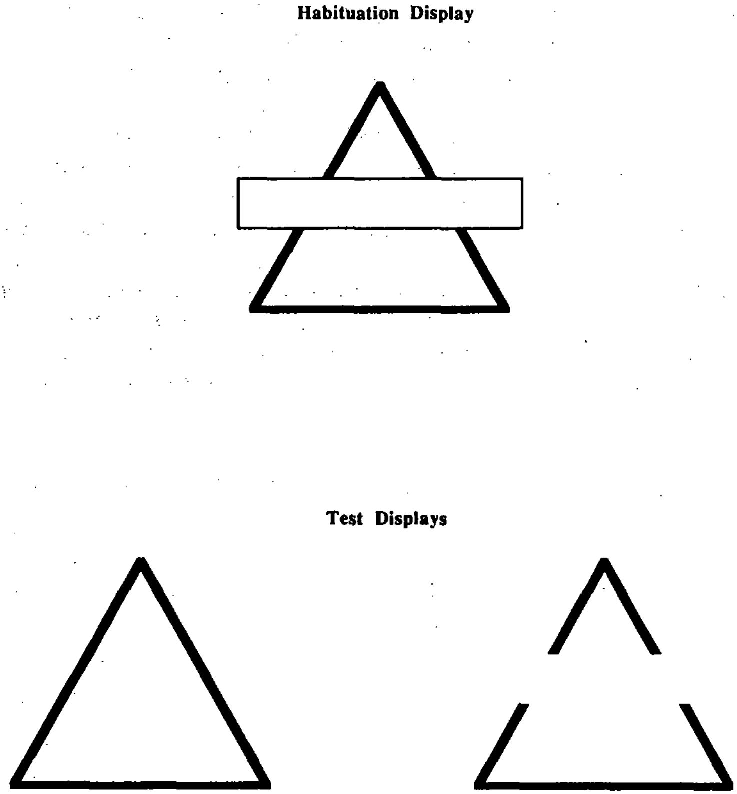

Figure 1. Schematic depiction of the displays for an experiment on infants' perception of the unity of a center-occluded object. The actual displays were composed of three-dimensional objects (Kellman & Spelke, 1983; adapted from Michotte et al, 1964).

Infant Perception of Object Unity

Philip Kellman and I attempted to test these theories by studying the abilities of prereaching, prelocomotor infants to perceive the unity of an object that is partly hidden. Our experiments (Kellman & Spelke, 1983) used a habituation of looking time method to investigate 4-month-old infants' perception of displays such as that in Figure 1: An object of a relatively regular shape with two visible ends and an occluded center.

Infants first were presented with a center-occluded object on a series of trials, until the time they spent looking at the occlusion display declined to a criterion of habituation: a 50% reduction in looking time. Then infants were shown two non-occluded displays: a complete object, connected behind the occluder to create the simplest possible form, and a fragmented object consisting of the visible surfaces from the original display. The non-occluded displays were presented on 6 alternating test trials, each of which began when the infant looked at the display and ended when he or she looked away. Infants in baseline control experiments received the same 6 test trials either without any habituation sequence or after habituation to an unrelated display. Total looking time to each test display was recorded by observers unaware of the particular display viewed on any trial. The test trial looking times of infants in the habituation and the baseline experiments were then compared.

The interpretation of test trial looking patterns in these experiments depends on the finding, obtained in hundreds of laboratories and verified in our own, that habituation is followed by longer looking at the test display that infants perceive as more different from the habituation display (see Spelke, 1985). If infants perceive an occlusion display as a mosaic of visible surfaces, therefore, the infants who are habituated to that display should look longer at the connected test display, relative to the infants in the baseline condition. If infants perceive a center-occluded object as one connected body, in contrast, then the infants habituated to an occlusion display should look longer at the fragmented test display, relative to baseline.

Experiments were conducted with a variety of occlusion displays (Figure 2). To our initial surprise, the findings of these experiments were not consistent either with empiricist or with Gestalt theories. Contrary to the predictions from most empiricist theories, habituation never generalized from a partly occluded object to a fragmented object with the same arrangement of visible surfaces: Young infants evidently do not perceive an object to end where its occluder begins. Contrary to Gestant theory, however, the pattern of findings obtained across a variety of experiments provided no evidence that infants perceive partly occluded objects by grouping visible surfaces into units that are maximally simple and regular.

More specifically, infants were found to perceive a partly hidden object as a connected unit if the ends of the object moved together behind the occluder. Any unitary translation of the object in three-dimensional space led infants to perceive a continuous object: Vertical translation and translation in depth had the same effect as lateral translation (Kellman, Spelke, & Short, 1986; Figure 3). Perception of a moving, center-occluded object was not affected by the object's configurational properties: Infants perceived a connected object just as strongly when the object's visible surfaces were asymmetric and heterogeneous in texture and color (Figure 2e) as when they formed a simple shape of a uniform texture and color (Figure 2a).

When infants were presented with a stationary, center-occluded object, their perception appeared to be indeterminate between a connected object and two object fragments: Infants dishabituated equally to the connected and fragmented test displays (Kellman & Spelke, 1983; Schmidt, 1985; Schwartz, 1982; Termine, Hyrnick, Kestenbaum, Gleitman, & Spelke, 1987).

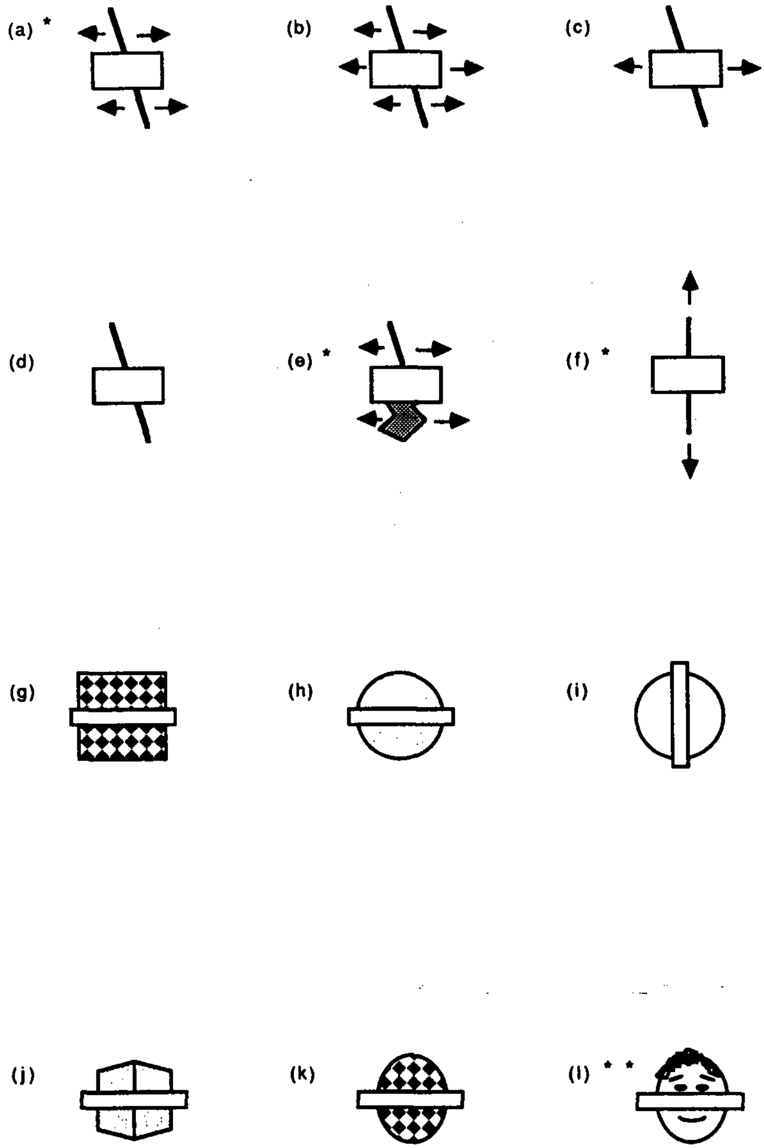

Figure 2. Schematic depiction of selected occlusion displays from experiments on infants' perception of partly hidden objects. *Arrows indicate the direction of motion for moving displays.* A single asterisk marks the displays for which 4-month-old infants perceived the occluded object as one connected body; a double asterisk marks the display for which 5- but not 4-month-old infants perceived a connected body [Kellman & Spelke, 1983 (a–e); Kellman et al, 1986 (f); Termine et al, 1987 (g: the occluded object was flat); Schmidt & Spelke, 1984 (h–j: the occluded objects were three-dimensional solids); Schwartz, 1982 (k–l: the occluded objects appeared in slide photographs)].

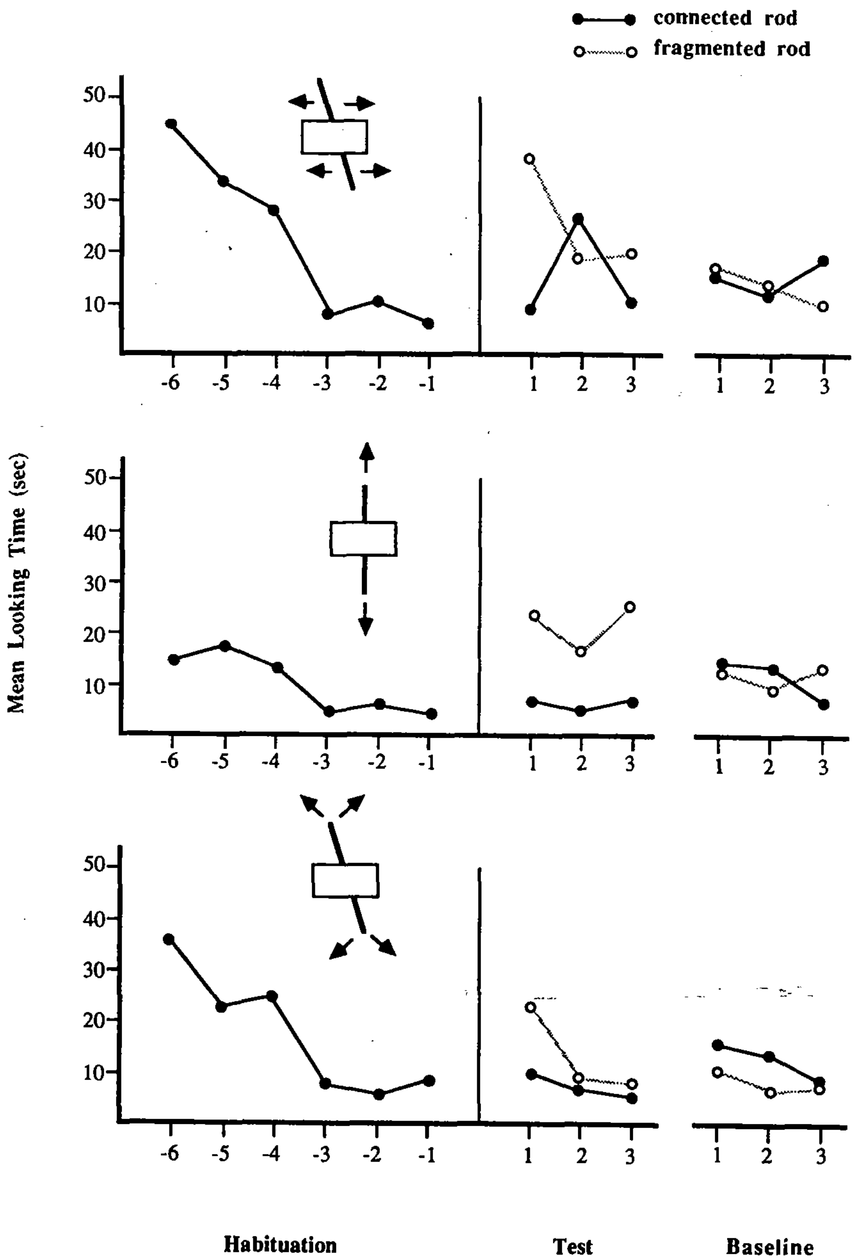

Figure 3. Looking time to complete and fragmented test displays after habituation to a center-occluded rod undergoing lateral motion, vertical motion, or motion in depth (Kellman & Spelke, 1983; Kellman et al, 1986). Infants in corresponding control conditions (right) showed reliably lower looking preferences for the fragmented rod.

A pattern of equal test trial looking was obtained, even when the object in the original habituation display had a regular shape and a uniform color and texture (Figures 2g-2k).

These findings contrast with the reports of adults, who were shown the same displays (Kellman & Spelke, 1983; Schmidt, 1985; see also Michotte, Thinès, & Crabbé, 1964). Adults' responses to center-occluded objects were affected both by motion and by static Gestalt properties: They tended to group partly occluded surfaces into the simplest possible forms, as Gestalt theory predicts. In contrast, the infants in our experiments were affected by motion alone: They exhibited no tendency to organize surfaces into maximally simple and regular units.

Infant Perception of Object Boundaries

Similar conclusions came from experiments focusing on 3- to 5-month-old infants' perception of object boundaries. Infants were presented with two separated, adjacent, or overlapping objects in a variety of arrangements (Figure 4). Perception of the objects' boundaries was investigated by means of four different methods. Some experiments focused on infants' earliest patterns of object-directed reaching, in order to determine what parts of a display infants tended to reach for as a whole (Hofsten & Spelke, 1985; Spelke, Hofsten, & Kesterbaum, 1989a). Other experiments investigated infants' apprehension of the number of objects in a display, by means of a habituation-to-number method (after Starkey, Spelke, & Gelman, 1983). Infants were habituated to a succession of displays that contained either one object or two visibly separated objects, and then they were tested for generalization to displays of two overlapping objects (Prather & Spelke, 1982). Still further experiments used a surprise method, in which infants were presented with a display of objects that moved in ways that either preserved or violated the objects' integrity and boundaries, and in which condition-blind observers judged whether infants showed signs of surprise during any of the motions (Spelke, Born, Mangelsdorf, Richter, & Termine, 1983). Finally, perception of object boundaries was studied by means of the habituation method described above: Infants were habituated to a display of overlapping objects, and then they were tested with displays of the same visible surfaces in new arrangements that either preserved or changed the objects' boundaries (Kestenbaum, Termine, & Spelke, 1987; Spelke, Jacobson, & Breinlinger, 1989a; Spelke, Jacobson, & Breinlinger, 1989b).

All the experiments provided evidence that young infants perceive object boundaries by detecting surface motions and surface arrangements. Infants perceived two objects as separate units when one object moved relative to the other object, even when the objects touched throughout the motion (Figure 4i). Infants also perceived two stationary objects as separate units when the objects were spatially separated on any dimension, including separation in depth (Figures 4a, 4c, & 4e).

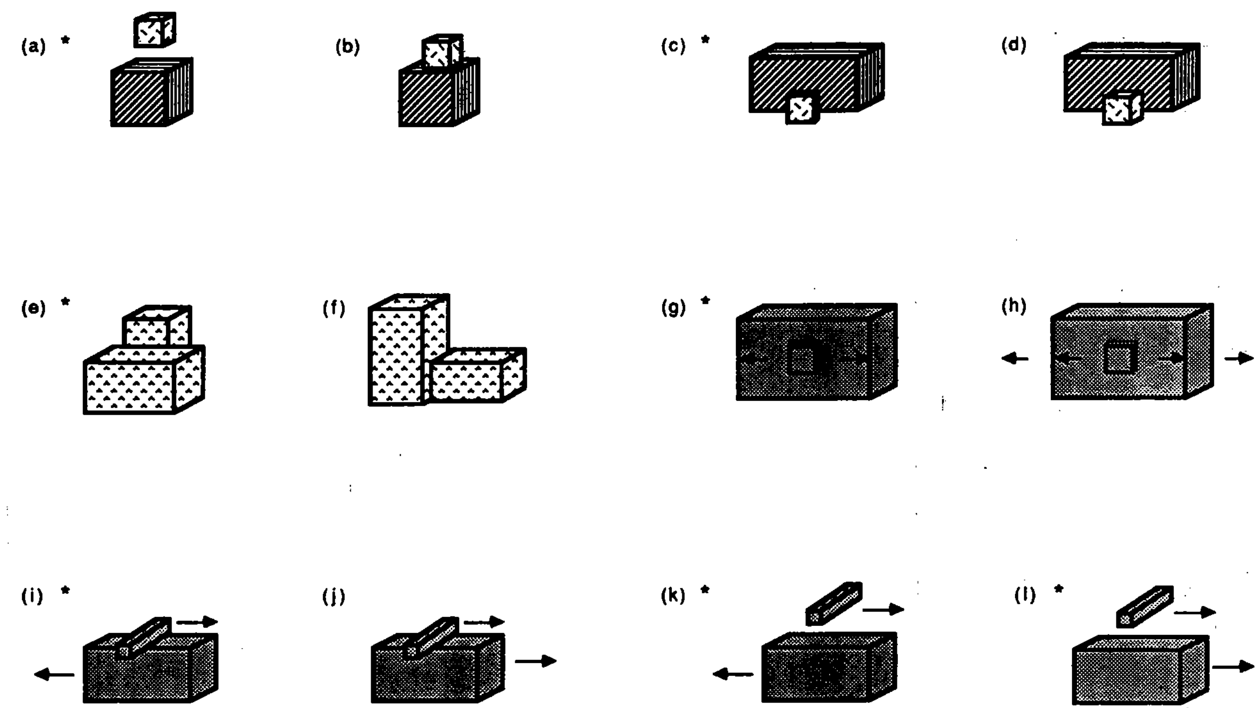

Figure 4. Schematic depiction of selected displays from experiments on infants' perception of object boundaries. Arrows indicate whether and how objects moved. The objects in (c), (e), (g), and (h) were separated in depth. Displays marked with an asterisk were perceived by 3- to 5-month-old infants as two separate objects; all other displays were perceived as one object [Kesternbaum, et al, 1987 (a–d); Prather & Spelke, 1982 (e–f); Hofsten & Spelke (g–h); Spelke et al, 1989a (i–l)].

In contrast, no experiment provided evidence that young infants perceive object boundaries by forming units that are maximally regular in their static configurational properties. When two stationary objects of different colors, different textures, different shapes, and misaligned edges were adjacent in the picture plane (Figure 4b) or in depth (Figure 4d), three-month-old infants perceived the two objects as one unit. These findings again contrasted with the findings of experiments with adults: Adult subjects shown the same displays perceived object boundaries by detecting not only surface motions and surface arrangements but also surface colors, textures, and forms (Kestenbaum, et al., 1987; Spelke, et al., 1989b; see also Koffka, 1935).

Detection versus Use of Gestalt Relations

One might ask whether infants' failure to respond to Gestalt relationships stems from limits on visual acuity or form perception. Research from a variety of laboratories, including our own, casts doubt on this possibility. For example, experiments provide evidence that young infants detect a misaligned contour in an array of elements with aligned contours, suggesting that they are sensitive to the Gestalt relation of good continuation (van Giffen & Haith, 1984). Other detection and discrimination experiments provide evidence that infants are sensitive to the homogeneity or heterogeneity of surface coloring (e.g., Fantz, Fagan, & Miranda, 1975) and to aspects of figural goodness such as symmetry (Bornstein, Ferdinandsen, & Gross, 1981). Indeed, infants have been shown to detect symmetry and/or contour alignment in some of the very displays presented in studies of object perception (Schmidt & Spelke, 1984).

Despite their sensitivity to Gestalt relations, infants do not appear to use these relations when they organize surfaces into objects. For example, the presence of detectably aligned contours on two sides of an occluder does not lead infants to perceive the contours as boundaries of a single, continuous object. These findings provide one example of the selectivity that Gelman (this issue) describes. When young infants organize a surface layout into objects, they are guided only by a subset of the surface properties and surface relationships that they can detect.

Gestalt Relations and Non-Accidentalness

Although the above experiments were motivated primarily by the Gestalt approach to object perception, they are relevant to a newer approach to perception based on the principle of non-accidentalness (Witkin & Tenenbaum, 1983). Geometric relationships such as collinearity and parallelism are unlikely to occur in retinal arrays through an accident of viewpoint; instead, they are usually projections of collinear or parallel edges in the visible surface layout. According to the principle of non-accidentalness, these relationships are especially informative about surfaces and objects, and they are to be given the non-accidental interpretation.

It is possible that young infants honor the principle of non-accidentalness when they perceive surfaces. For example, infants may interpret collinear edges in the retinal array as collinear edges in the surface layout. Our research suggests, however, that properties such as collinearity and parallelism do not influence infants' perception of the unity and boundaries of objects. For young humans, at least, the organization of the visual world into objects does not appear to center on non-accidental geometric properties of retinal arrays.

Development of Gestalt Perception

Finally, we may ask whether Gestalt effects on object perception develop in a global or a piecemeal fashion. If these effects reflect one general tendency to maximize perceptual simplicity, as the Gestalt psychologists believed, then there should be one time in development when humans begin to organize visual arrays in accord with Gestalt principles. In contrast, if Gestalt principles reflect children's learning about objects and their properties, as empiricist theorists have proposed, then those principles might come to influence object perception at different times for different kinds of displays.

Experiments conducted with Schmidt investigated when infants and children begin to perceive partly occluded objects in accord with the Gestalt relations of good continuation and similarity (Schmidt, 1985; Schmidt, et al., 1986). Subjects were presented with center-occluded nonsense forms. In some displays, a form's visible surfaces were homogeneously colored and coplanar, and its edges were collinear at the point of occlusion (Figure 5a). In other displays, a form's visible surfaces differed in color and were nonplanar, and its edges converged at the point of occlusion so that a linear extrapolation of each edge behind the occluder produced two distinct forms separated by a gap (Figure 5b). Adults judged that displays of the first kind consisted of a single form and that displays of the second kind consisted of two distinct forms (Schmidt, 1985). In three separate tasks requiring object matching, naming, and counting, 2½-year-old children also were found to perceive these displays in accord with Gestalt principles (Schmidt, 1985).

To investigate infants' perception of the displays, separate groups of 5-and 7-month-old infants were habituated to each of the occlusion displays in Figure 5, and then infants were presented with non-occluded displays of one versus two forms created by extrapolating or connecting the forms' visible edges in straight lines (see Figure 5). At 5 months of age, the infants in both habituation conditions dishabituated equally to the two test displays. This finding suggested that perception of both displays was indeterminate and failed to accord with the principles of good continuation and similarity. At 7 months of age, infants who were habituated to the display with homogeneous coloring, coplanar surfaces, and aligned edges generalized habituation more to the connected test display. The ability to perceive the unity of this display appears to develop between 5 and 7 months. In contrast, 7-

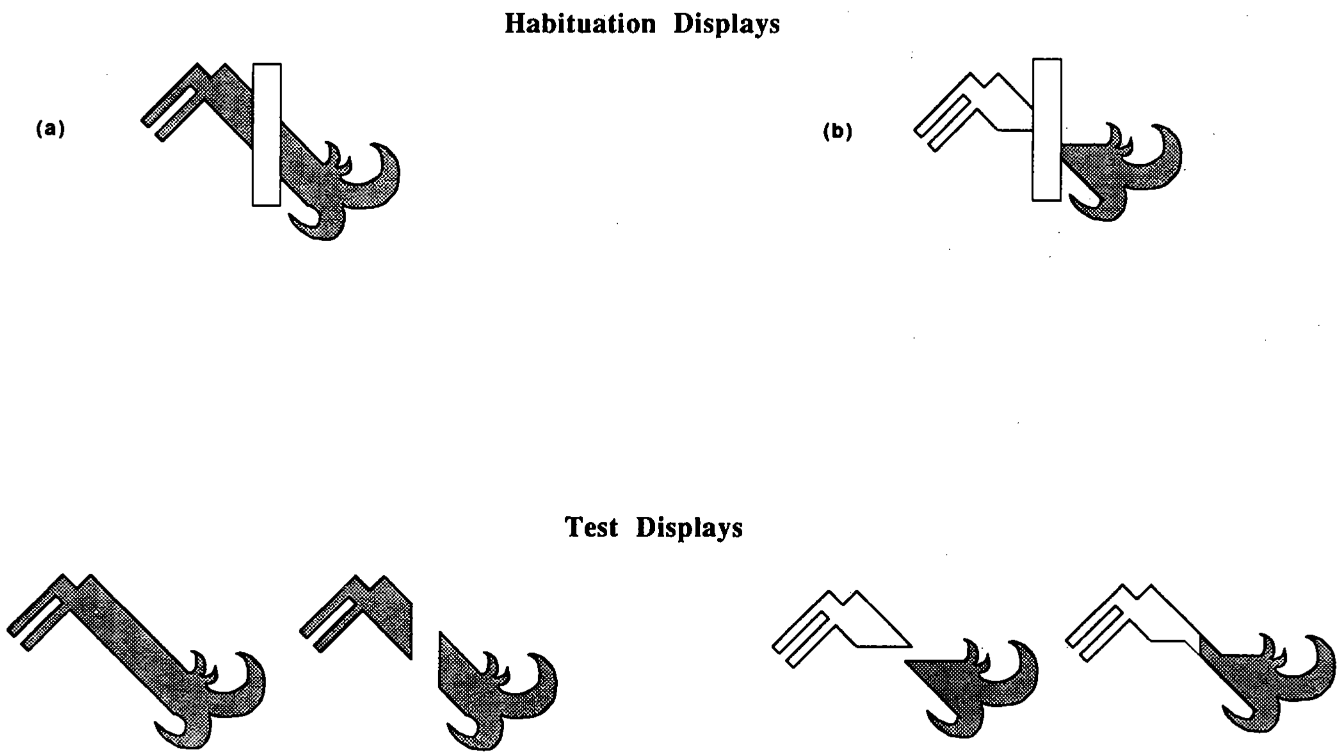

Figure 5. Displays for experiments on the development of abilities to perceive partly hidden objects in accord with relations of good continuation and similarity (Schmidt et al, 1986).

month-old infants who were habituated to the display with heterogeneous coloring, non-planar surfaces, and converging edges dishabituated equally to the two test displays. The ability to perceive the distinctness of the visible surfaces in this display evidently develops between 7 and 30 months (Schmidt, Spelke, & LaMorte, 1986).

Although many aspects of the development of Gestalt perception remain to be investigated, these findings suggest that there is no single time in development when humans begin to perceive objects by maximizing figural goodness. What appears to be a single, general tendency to group visual arrays into units that are maximally simple and regular may depend, instead, on a host of separate analyses of particular kinds of object arrays. Children may begin to perform these analyses as they learn about objects and their likely properties, as Helmholtz (1925) and Brunswik (Brunswik & Kamiya, 1953) proposed. In any case, Gestalt effects on object perception do not appear to reflect the maturation of one general tendency to maximize the regularity of the perceived world.

OBJECT PERCEPTION AS A LATER PROCESS

Our next experiments returned to the positive findings from the research with young infants: Infants perceive the unity and boundaries of objects by detecting the spatial arrangements and motions of surfaces. These experiments were undertaken to investigate the processes that accomplish this task. In particular, they focused on the locus of the processes of object perception: Does object perception in infancy depend on relatively peripheral grouping processes that apply to low-level representations of visual arrays, or does it depend on processes that are more central? To address this question, experiments have investigated further the conditions under which young infants perceive visible objects in moving displays, they have investigated object perception in a different perceptual modality, and they have begun to investigate infants' apprehension of objects that move fully out of view.

Proximal versus Distal Motion in the Perception of Object Unity

Several of our earlier findings had suggested that processes of perceiving objects occur more centrally than processes of perceiving three-dimensional surface arrangements and motions. For example, infants were found to perceive the unity of a center-occluded object by detecting any common translatory motion of its surfaces, including translation in depth (Kellman et al., 1986). Moreover, infants were found to perceive the boundary between two objects by detecting any spatial separation between the objects, including separation in depth (Hofsten & Spelke, 1985; Kestenbaum et al., 1987). These findings motivated the next study of the effects of motion on perception of partly hidden objects (Kellman, Gleitman, & Spelke, 1987). We investigated whether infants apprehend the unity of moving, center-occluded objects by detecting patterns of image displacement in a representation of the two-dimensional visual array or patterns of surface motion in a representation of the three-dimensional surface layout.

Four-month-old infants were presented with a center-occluded rod while they themselves were seated in a chair that moved back and forth in an arc (Figure 6). In one condition, the rod was stationary, and its image was displaced in the visual field as the baby moved. In the other condition, the rod moved conjointly with the baby so as to cancel this image displacement. The extent and the speed of the infant's motion were such that the first condition presented about the same amount of proximal displacement, and the second condition presented about the same amount of distal displacement, as in the earlier experiments with stationary infants and moving objects. Perception of the continuity of the rod was investigated, for each condition, by means of the habituation method.

The principal findings appear in Figure 7. Infants in the proximal motion condition showed the same looking patterns as the infants in previous experiments who were habituated to stationary objects: They looked equally at the complete and broken test rods, as if they had not perceived the center-occluded rod as a connected unit. In contrast, infants in the distal motion condition showed the same looking patterns as the infants in previous experiments who were habituated to laterally moving objects: They generalized habituation to the connected rod and looked longer at the fragmented rod, as if they had perceived the center-occluded rod as one connected unit.

This experiment provides evidence that the mechanisms of object perception operate on representations of the distal motions of surfaces, not on representations of the proximal motions of elements in the retinal array. That finding suggests, in turn, that the organization of the visual world into objects occurs more centrally than the perception of space and motion. First infants perceive the arrangements and motions of surfaces in a three-dimensional layout. This representation then serves as input to the processes of object perception, which organize the perceived surface layout into spatially connected bodies that move as wholes.

Haptic Perception of Object Unity and Boundaries

The next studies, with Streri, began to investigate whether infants apprehend objects by means of separate, modality-specific mechanisms or by means of a single mechanism that accepts input from different perceptual systems. The studies focused on object perception in the haptic mode, investigating whether infants perceive the unity and boundaries of objects under the same conditions when they feel objects as when they see them. If a single set of mechanisms underlies object perception, we reasoned, then perception should succeed and fail under the same conditions in the haptic

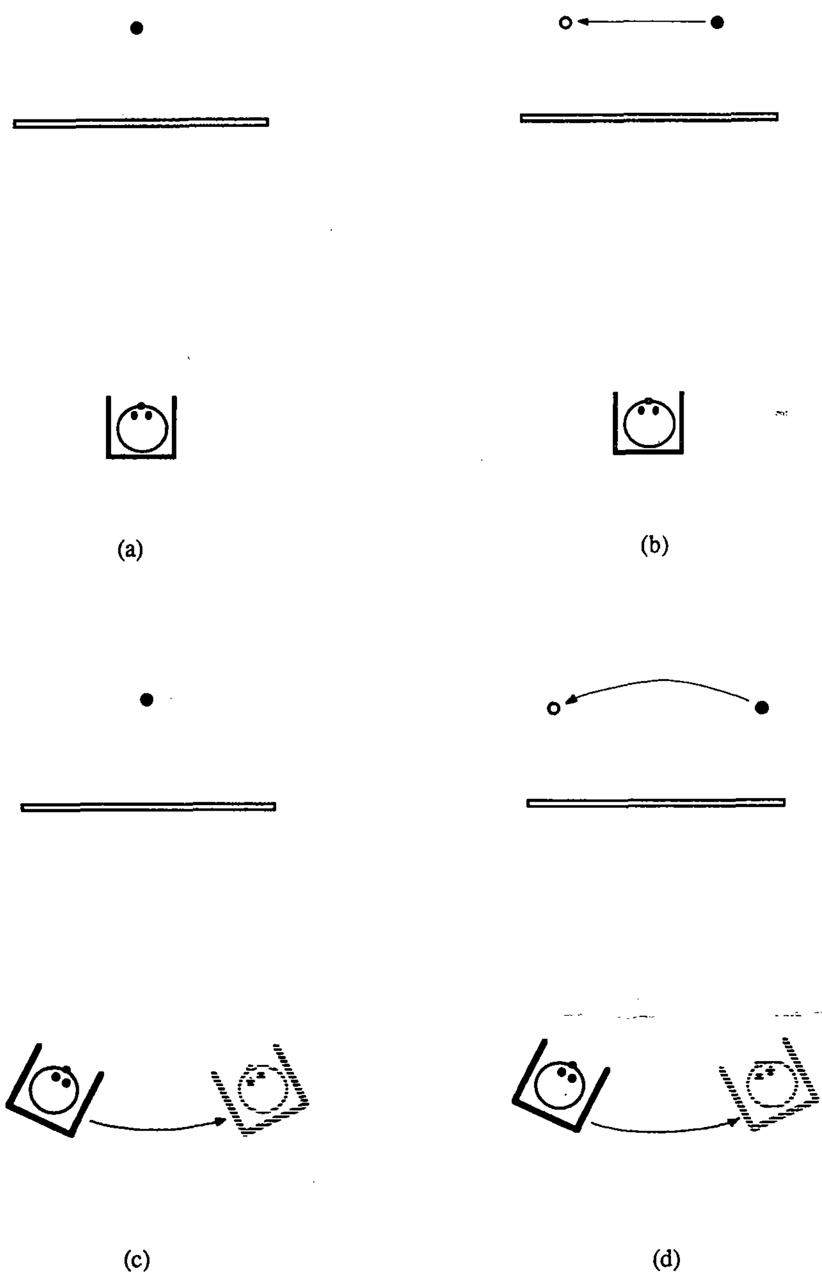

Figure 6. Top view of displays and apparatus for an experiment on perception of object unity during observer motion. Arrows indicate the path of object and/or observer motion (Kellman, et al, 1987).

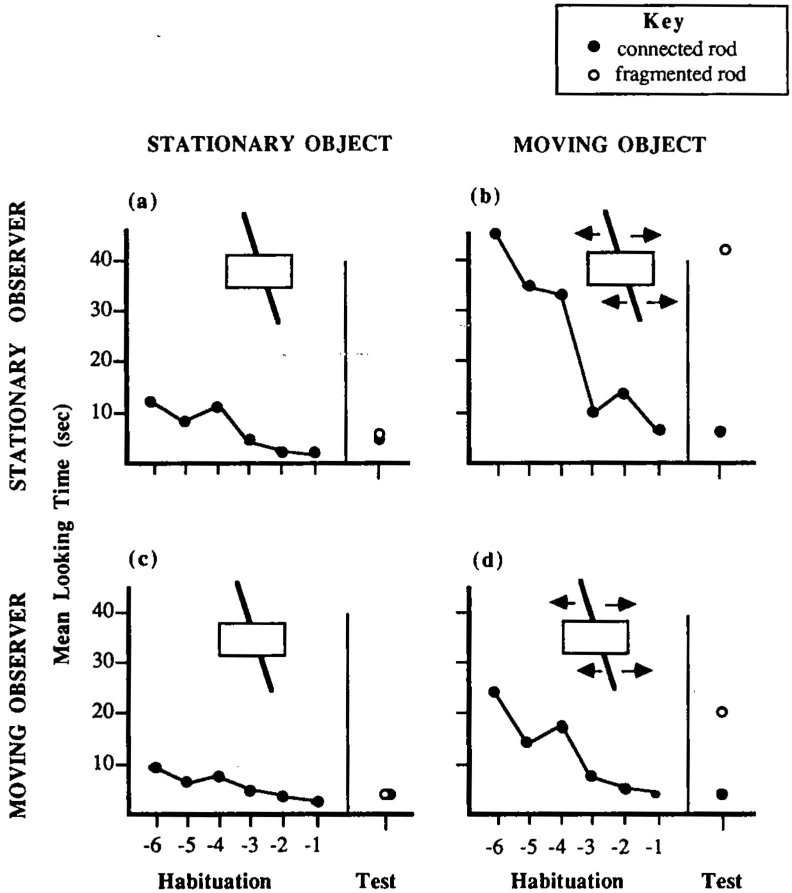

Figure 7. Looking time to complete and fragmented test displays, after habituation to stationary or moving center-occluded objects by stationary or moving observers. The observer motion in (c) created image displacement similar to the image displacement in (b); the observer motion in (d) cancelled the image displacement from object motion [Kellman & Spelke, 1983 (a–b); Kellman et al, 1987 (c–d)].

mode as in the visual mode, as long as the input to the perceptual mechanisms is not degraded by peripheral limitations.

In our first experiments (Streri & Spelke, 1988), 4-month-old infants held two rings, one in each hand, under a cloth that blocked their view of the rings and of their own bodies (Figure 8). The rings could be moved independently in one condition, and they could only be moved together rigidly in the other condition. Infants were allowed to move the rings at will, and they did so quite actively (without, however, touching the area between the rings).

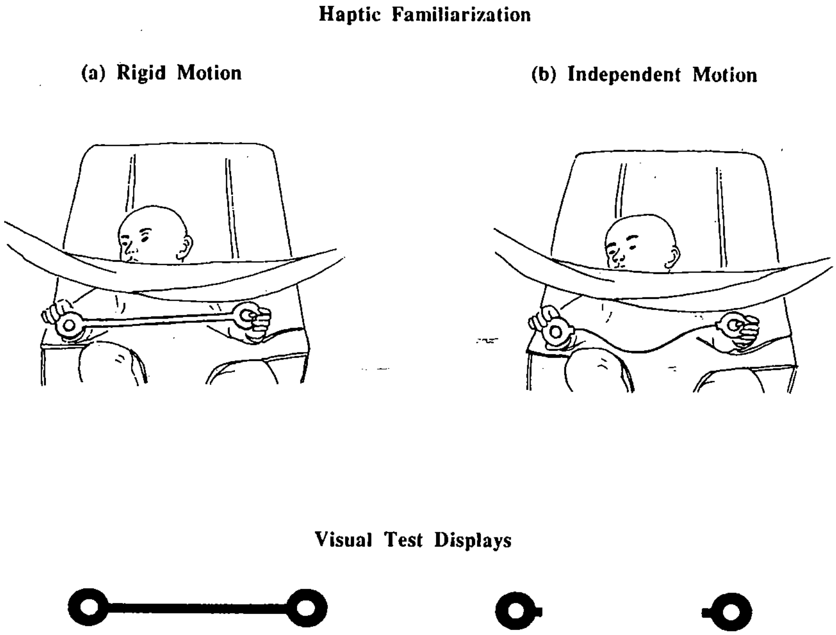

Figure 8. Displays and apparatus for an experiment on haptic perception of object unity and boundaries (Streri & Spelke, 1988).

Half the infants were habituated to each haptic ring assembly, and then the infants were shown alternating visual displays of connected and separated rings undergoing no distinctive motion. A separate, baseline control group of infants viewed the test displays without prior habituation. Habituation to the independently moveable rings was followed by longer looking at the connected display, relative to baseline. This finding provides evidence that the infants perceived the independently moving rings as distinct objects. In contrast, habituation to the rigidly moveable rings was followed by longer looking at the separated display, relative to baseline. This finding provides evidence that the infants perceived the commonly moving rings as a single object. Motion appears to specify the unity and boundaries of objects in the haptic mode.

Subsequent experiments suggested that Gestalt configurational properties fail to influence infants' organization of felt arrays (Streri & Spelke, 1989). Infants were allowed to hold two rigidly movable rings, as in the previous study. In one experiment, the two rings were the same in substance (wood or foam rubber), weight (heavy or light), texture (smooth or rough), and shape (square or round). In the other experiment, the two rings differed on those dimensions. Perception of the object boundaries was tested by habituating one group of infants to a haptically presented ring assembly and then showing those infants, and infants in a baseline control condition, visual displays of the two rings with a connection or a gap between them.

The results provided evidence that infants perceived each of the ring assemblies as one connected object. Comparisons across the experiments indicated no effect of figural goodness on haptic object perception. These findings contrast with the findings of an experiment with adults (Streri & Spelke, 1989). Adult subjects were presented with enlarged versions of the same ring assemblies, and they were asked to judge how many objects they felt in each assembly. These judgments appeared to be affected both by motion and by figural goodness: Adults judged that each assembly consisted of a single connected object, but their judgments were reliably stronger for the assemblies that formed an object of a homogeneous substance and simple shape. For adults, in contrast to infants, haptic object perception is affected by the static Gestalt properties of displays.

In summary, experiments on haptic perception provide evidence that infants apprehend objects under the same conditions when they feel objects as when they see them. This finding is consistent with the thesis that a single, amodal process underlies the organization of surfaces into objects. The experiments do not prove that object perception results from an amodal process: It is possible that 4-month-old infants apprehend objects by means of separate visual and haptic mechanisms that succeed and fail, by coincidence, under the same conditions. The simpler hypothesis, however, is that the process for apprehending objects is central enough to accept input from different perceptual modes.

Apprehension of Object Identity

Our next studies investigated whether young infants are able to apprehend the persisting identity of objects that move fully out of view. One way to apprehend object identity, much discussed in philosophy, is to consider the apparent continuity or discontinuity of the path of object motion (e.g., Hirsch, 1982). For adults, physical objects move on connected paths; they cannot jump discontinuously from one place and time to another. Our studies (Spelke & Kestenbaum, 1986; Spelke, Kestenbaum, & Wein, 1989c) investigated whether 4-month-old infants apprehend the identity or distinctness of objects in accord with this constraint.

Infants were presented with events in which one or two objects moved behind two screens (Figure 9). In one event, a single object moved continuously across the display, disappearing behind each screen in turn. The other event was the same except that no object appeared between the screens: An object disappeared behind the first screen and then, after a pause, an object reappeared from behind the second screen. Adults judged that the first event involved one object moving continuously across the display, and that the

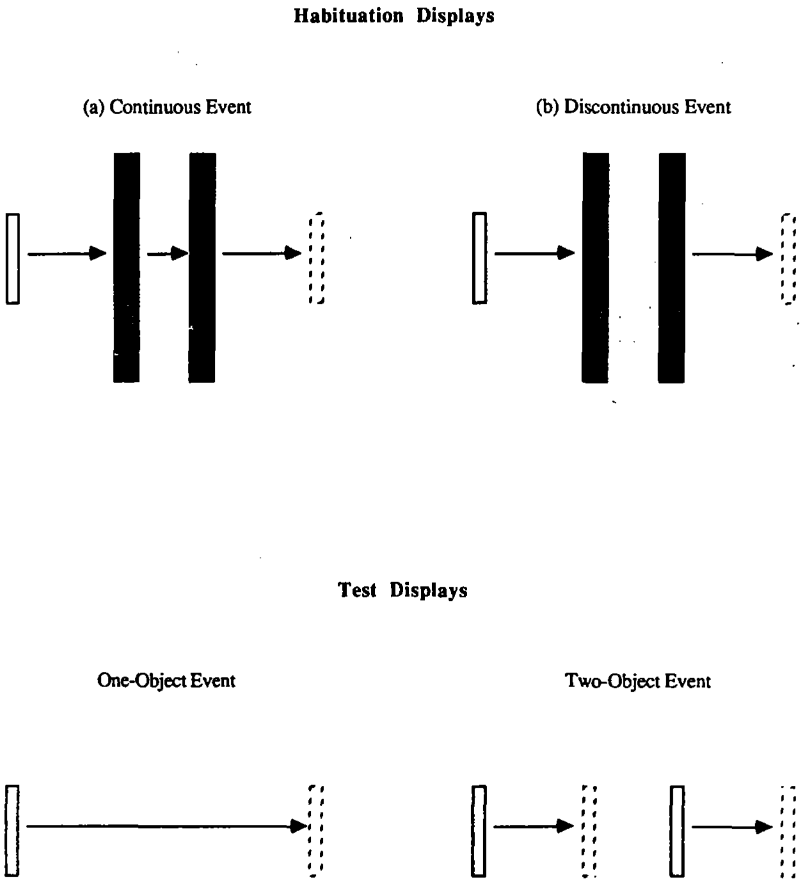

Figure 9. Displays for an experiment on infants' apprehension of object identity over occlusion. Solid and dotted lines indicate the initial and final positions of the object(s) after one half-cycle of the event (Spelke & Kestenbaum, 1986).

second event involved two objects moving continuously on the sides of the display (Spelke et al., 1989c).

To see how infants perceived these events, separate groups of 4-month-old infants were habituated to each event, and then all the infants were given test trials in which one or two objects appeared without the occluders, undergoing similar motions. The infants who were habituated to the continuous event generalized more to the one-object display, whereas the infants who were habituated to the discontinuous event generalized more to the two-object display (Spelke & Kestenbaum, 1986). A replication of this experiment with a baseline control condition revealed that the preference for the one-object display shown by the infants in the discontinuous condition reliably exceeded the baseline preference for that display, whereas the preferences in the continuous condition did not differ from baseline (Spelke et al., 1989c). Taken together, the experiments provide evidence that the presence of a visible discontinuity in object motion led infants to perceive two distinct objects, in accord with the principle that objects move on connected paths.

Our last experiment suggested that infants fail to apprehend object identity in accord with any tendency to maximize the smoothness and regularity of object motion. Infants observed an object that moved in and out of view on alternate sides of one wide screen. In one condition, the object's occlusion time was appropriate to its visible speed; in other conditions, the occlusion time was either one-third as long or it approached zero. Adults have been reported to perceive one object in events of the first type, in accord with Gestalt principles (Michotte et al., 1964). Indeed, adult subjects who viewed the present displays reported an impression of one object more often for the event with the appropriate occlusion time than for the other events (Spelke et al., 1989c). Infants, in contrast, did not appear to perceive any of the events as involving a determinate number of objects. Test trial looking preferences in the different experimental conditions did not differ from one another or from baseline (Spelke et al., 1989c).

These experiments provide evidence that infants apprehend object identity by analyzing the connected path of object motion, in accord with the principle that object motion is continuous over space and time. The experiments provide no evidence that infants apprehend object identity by analyzing the apparent constancy or change in speed of object motion, in accord with the principle that object motion is maximally smooth and regular. Gestalt principles again failed to influence young infants' response to objects.

PRINCIPLES OF OBJECT PERCEPTION

In summary, young infants can sometimes perceive the unity of partly hidden objects, the boundaries of adjacent objects, and the identity or distinctness of objects that move fully out of view. The mechanisms that accomplish these tasks appear to be central in three respects: (1) They take as input representations of three-dimensional surface arrangements and motions, (2) they are amodal, and (3) they yield representations of parts or states of an object that cannot be seen directly. Let us now consider one partial account for these findings.

I propose that young infants perceive objects by first forming a representation of the visible surface layout. This representation is viewer-centered; it includes information about the distance of each surface point in the visual field and about the displacement of that point over the interval of observation. If the layout is composed of enduring surfaces, then most surface points that are adjacent in the two-dimensional projection of the layout will be nearest neighbors in depth, and they will remain nearest neighbors as they move. These "connected surface points" are central to the perception of object unity.

The perceived surface layout is divided into unitary, bounded, and persisting objects by mechanisms operating in accord with the principles of cohesion, boundedness, rigidity, and no action at a distance. According to the *cohesion principle,* two surface points lie on the same object only if the points are linked by a path of connected surface points. When two surfaces are separated by a spatial gap (as in Figure 4a) or undergo relative motions that alter the adjacency relations among points at their border (as in Figure 4i), the surfaces lie on distinct objects.

The cohesion principle implies that all points on an object exist continuously during the interval of observation, because surface points can be grouped onto one object only if they are connected (and therefore present) throughout that interval. If the motion of an enduring surface point is represented as continuous,[1] then the cohesion principle further implies that all points on an object move on connected paths over space and time. When surface points appear at different places and times such that no connected path could unite their appearances (as in Figure 9b), the surface points do not lie on the same object.

According to the *boundedness principle,* two surface points lie on distinct objects only if no path of connected surface points links them. That is, every path between two points on distinct objects includes at least one pair of two-dimensionally adjacent surface points that either are separated in depth or become separated over motion. These points define an object boundary. When surfaces are neither spatially separated nor separately moving (as in Figures 4b, 4d, 4f, and 4j), no boundary lies between them, and they are part of the same object.

The boundedness principle implies that two distinct objects cannot contain the same surface point, because there can be no boundary between a surface point and itself. If humans represent at most one surface point at each three-dimensional location in the layout,[2] the boundedness principle implies that two objects cannot occupy the same place at the same time. Thus, two distinct objects cannot interpenetrate.

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[1] Research on apparent motion appears to support this assumption. When two stationary displays are presented in alternation under spatio-temporal conditions appropriate to the perception of motion, human adults perceive the motion as continuous, despite the absence of a continuously moving stimulus (e.g., Anstis, 1978).

[2] Research on perceived transparency suggests that humans can represent two distinct surfaces in the same two-dimensional location in the visual field. In these cases, however, the surfaces appear to lie at different depths (e.g., Gibson, Gibson, Smith, & Flock, 1959; Metelli, 1974; Ullman, 1979).

The principles of *rigidity* and *no action at a distance* specify further connections and separations among surfaces. According to the former principle, objects are interpreted as moving rigidly if such an interpretation exists. Thus, two surfaces that undergo different rigid motions are perceived as distinct bodies rather than as one body with a non-rigid center, unless such a center is detected directly (Figures 4g and 8b). According to the latter principle, separated objects are interpreted as moving independently of one another if such an interpretation exists. Thus, two surfaces that undergo a common rigid motion are perceived as connected, in the absence of a detectable separation between them (Figures 2a, 2e, 2f, 4h, and 8a; compare Figure 4l).[3]

Two aspects of this account deserve mention. First, the principles of cohesion, boundedness, rigidity, and no action at a distance do not permit a complete segmentation of visual arrays into objects. For example, they fail to capture the unity of any stationary, center-occluded object, and they fail to recover the boundary between any two objects that are adjacent and that move together, such as a horse and rider (Marr, 1982). If the general process of object segmentation accords only with these principles, it must be supplemented by further processes, such as processes for finding object boundaries by recognizing objects of particular kinds.

Nevertheless, a partial segmentation of surfaces into objects might ease the task of object recognition by limiting the potential matches of object models to visual arrays. If an object model is to match any part of a visual scene, the boundaries of the model can be constrained to lie on or within the boundaries of a cohesive, bounded, and independently moving body.[4] Consider the example of the horse and rider. Although the principles of cohesion, boundedness, and no action at a distance do not specify where a horse ends and its rider begins, they limit the possible boundaries of those objects. No object model could correspond to the horse's moving leg and the stationary ground beneath it, or to the rider's head and a tree behind it. Despite its incompleteness, therefore, a general process for organizing surfaces into objects might contribute to the process of forming more complete and meaningful representations of visual scenes (see also Lowe, 1987).

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[3] My previous attempts to characterize infants' perception and knowledge of objects centered on four principles: cohesion, boundedness, spatiotemporal continuity, and solidity or substance (e.g., Spelke, 1988). In the present account, continuity and solidity are implied by cohesion and boundedness, respectively. In addition, previous formulations failed to distinguish the principles of rigidity and no action at a distance from the principles of cohesion and boundedness, respectively.

The present account is incomplete. An adequate theory of object perception would include a more detailed characterization of the representation of surfaces and of the observation interval over which surface arrangements and motions are analyzed. Such a theory would also include further treatment of the representation of occluded surface points and the interpretation of non-rigid motions.

[4] This constraint implies that no single model is used to recognize instances of the small class of "objects" composed of two or more unconnected bodies (e.g., bikinis that are not being worn).

Second, the present account suggests a link between processes of perceiving objects and processes of reasoning about the physical world. In this respect, it differs from other approaches to perceptual organization. Approaches based on principles of Prägnanz or non-accidentalness focus on projective or metric properties of two-dimensional arrays. According to these approaches, perceptual organization either reflects general aspects of the behavior of neural systems when they are activated by a retinal array, or it reflects constraints on the ways a three-dimensional surface layout is projected onto a two-dimensional surface. In contrast, the present approach focuses primarily on topological properties of three-dimensional arrays and on changes in those properties over motion. According to this approach, object perception reflects basic constraints on the motions of physical bodies. Bodies move as connected wholes, they move on connected paths, they do not interpenetrate as they move, they tend not to deform as they move, and they tend to move separately from one another unless they come into contact.

The present analysis thus raises the possibility that abilities to perceive objects are related to abilities to reason about objects and their behavior (Spelke, 1988). Recent research on infants' inferences about the motions of occluded objects supports this possibility. Young infants appear to infer that occluded objects move on connected paths through unobstructed space: Objects do not jump over or pass through other objects or surfaces (Spelke, Macomber, Turner, & Breinlinger, 1989d; see also Baillargeon, 1986, in press). Young infants also appear to infer that occluded objects maintain a constant size and shape as they move: They do not deform while hidden (Spelke et al., 1989d; see also Baillargeon, 1987). Finally, young infants appear to appreciate that objects act upon each other only when they come into contact (Leslie, 1988). Inferences about object motion appear to accord with the principles by which infants perceive object unity, object boundaries, and object identity.

DEVELOPMENTAL CHANGES IN OBJECT PERCEPTION

Even if one accepted the above suggestions, one might question their relevance for studies of object perception in human adults or in machine vision. Object perception might change radically over the course of development. In that case, studies of infants would reveal little about how adults perceive objects. Since adults perceive objects far more effectively than infants, studies of infants might then suggest little of value to designers of artificial vision systems.

I suggest, in contrast, that development does not bring fundamental changes in object perception. Instead, new ways of apprehending objects enrich and reinforce the infant's earlier developing abilities. If this suggestion is correct, then studies of infants could shed light on perceptual processes of importance to students of human and machine vision. In particular, the processes by which infants perceive objects might serve as a basis for adults' remarkable capacities for object perception and recognition.

Development of Gestalt Perception and Object Recognition

The clearest case of developmental change in object perception concerns the emerging ability to perceive objects in accord with Gestalt relationships. As noted, developmental research suggests that infants learn in a piecemeal fashion to perceive objects by detecting these relationships. New ways of apprehending object unity, boundaries, and identity may join the infant's earlier-developing abilities through a learning process that the earlier abilities render both necessary and possible.

Infants need to develop new ways to perceive objects, because their initial abilities are so limited. Especially after the development of object-directed reaching at about 4½ months, infants need to discover properties of objects that are manifest in stationary arrays and that indicate what parts of an array can be separately moved and manipulated. Relations such as surface planarity, edge alignment, and color similarity could serve this purpose, if the infant can learn to use them.

But can children learn to use these relations? Following Kant (1929), Köhler and other Gestalt psychologists argued that these relations cannot be learned, because of the paradox of the "experience error" (Gottschaldt, 1967; Köhler, 1929). What one learns about a scene depends on how one organizes that scene: A child cannot learn about the properties of an object, unless he or she can already perceive the object as a stable entity with properties to be discovered. How then could children learn the Gestalt principles of organization—the principles that supposedly defined objects and governed all learning?

Research with infants suggests an answer. If infants have unlearned abilities to organize surface arrays into bodies that are cohesive, bounded, and independently movable, then infants will be able to perceive the objects that surround them under certain auspicious conditions. When infants perceive an object, they will be in a position to observe other properties of the object, such as its texture and shape. Thus, infants may discover that many objects have simple shapes, smooth contours, and uniform colors and textures. This learning might lead infants to perceive the boundaries of stationary objects in accord with Gestalt relations such as color similarity and good continuation.

In addition, infants who perceive an object by detecting surface arrangements and motions will be in a position to develop models of the object. These models might allow infants to recognize the object, and other objects of its kind, when it is stationary. In this way, infants could supplement their initial segmentation of a surface array with the finer segmentation that object recognition processes can provide. Gestalt effects on object perception might conceivably arise from a model-based segmentation of surface arrays, if object models exemplify Gestalt relations such as symmetry and good continuation.

Research by Schwartz (1982) suggests that model-based recognition comes to influence object perception during the first months of life. Using Kellman's method, Schwartz investigated 4- and 5-month-old infants' perception of a center-occluded photograph of a human face or face-shaped, nonsense form (Figures 2k & 2l). Her experiment provided evidence that at 5 months (but not 4 months) infants perceived the face as a connected object. Perceptual completion appeared to be specific to the face: The nonsense form was not perceived as a connected object at either age. Between 4 and 5 months, infants may begin to use at least one object model to perceive the unity of a stationary object that is partly hidden.

Whether infants learn relations such as good continuation directly, or learn models for objects that exhibit those relations, learning will allow infants to perceive object unity, boundaries, and persistence in situations that previously were ambiguous or misleading. This learning is not likely to overturn the infant's initial means for perceiving objects, however, for the reason Köhler emphasized. If the initial mechanisms for perceiving objects lead infants to organize surface arrays into cohesive, bounded, independently moving bodies, then those are the bodies that infants will learn to perceive more effectively. Initial principles for organizing the perceptual world may be enriched by the growth of knowledge. Those principles will tend to perpetuate themselves over the learning process, however, because they served to select the entities about which children learn.

Intuition and phenomenal experience support the view that cohesion, boundedness, rigidity, and no action at a distance are central properties of physical bodies for adult viewers. In particular, consider what adults perceive when these properties are placed in conflict with static configural relations. When adults view a stationary surface layout, we are inclined to perceive objects by maximizing figural goodness. This perception gives way, however, if different parts of what had seemed to be a simple and regular body split apart and move in different directions. Perceptual organization follows the continuous motion of the display, not its colors and forms (see Kahneman & Henik, 1981). Although simplicity of form and uniformity of substance are characteristic properties of many objects, they are neither necessary nor sufficient for perception of object unity, boundaries, and persistence.

Mature Processes of Perceiving Objects

If development enriches object perception without fundamentally changing it, then studies of infancy can shed light on processes of object perception in human adults. In particular, the findings described above support three proposals about mature processes of object perception.

The first proposal concerns the relation of object perception to surface perception. Visual arrays are organized into objects only after they are represented as a three-dimensional layout of surfaces undergoing three-dimensional motion. This proposal places object perception far from elementary processes of edge-detection (e.g., Marr, 1982) and texture segmentation (e.g., Beck, Prazdny, & Rosenfeld, 1983; Julesz, 1975), despite some superficial resemblances among the three types of process. If object segmentation occurs after perception of surface distance and motion, the segmentation process may avoid some of the problems that arise if object boundaries are sought in lower-level representations of the two-dimensional visual array (see Marr, 1982). At the same time, this segmentation process appears to reduce the problems that could arise if no general process of perceptual organization were allowed to operate (see Köhler, 1929; Witkin & Tenenbaum, 1983).

The second proposal concerns the relation of object segmentation to object recognition. The general process for perceiving objects operates before processes for recognizing objects of particular kinds. Its partial segmentation of visual arrays could serve as input to object recognition processes, which complete its work. I have suggested (with Lowe, 1987, and others) that a general process of object segmentation could facilitate the task of object recognition by limiting the number of potential matches of object models to visual arrays. A general process of object segmentation could also enable perceivers to develop models for new kinds of objects. It remains to be seen, of course, whether effective systems for recognizing objects or learning object models can be designed to operate on the input envisaged here.

The final proposal concerns the relation of object perception to physical knowledge. The research reviewed above suggests that object perception accords with principles by which humans reason about the physical world. Infants appear to honor the principles of cohesion, boundedness, rigidity, and no action at a distance when they predict how a hidden object will move and when they infer the source of a visible object's motion (Baillargeon, in press; Leslie, 1988; Spelke et al., 1989d). Adults also honor these principles in our commonsense physical reasoning. It is possible, therefore, that the principles by which infants perceive objects come to be deeply embedded in human thinking. In that case, an understanding of object perception may contribute some day to an understanding of physical knowledge.

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