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The origins of physical knowledge

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Overview

My research has focused on the ability of young infants to organize the perceptual world into physical objects. Infants, we have found, have considerable abilities to apprehend objects in visual scenes: they can sometimes perceive the unity and continuity of an object that is partly hidden, the boundaries between two objects that send overlapping images to the eyes, and the persisting identity of an object that moves fully out of view. Our evidence suggests, however, that infants do not perceive the unity, boundaries, and persistence of objects under all the conditions that are effective for adults. This finding is of special interest, because a consideration of the nature and limit of infants' abilities could shed light on the mechanism by which objects are apprehended, by mature humans as well as by infants. Our research suggests that this mechanism is surprisingly central—so central that it may be misleading to say that objects are *perceived*. Objects may be known, instead, by virtue of an early developing *theory* of the physical world. This chapter will review some of the research that has led to this suggestion, and then it will attempt to characterize the infant's physical theory and its role in apprehending objects. Finally, I will consider some of the ways in which the infant's theory might be changed by the acquisition of further physical knowledge, with and without benefit of language.

Perceiving objects as unitary and bounded

At its outset, our research was guided by the view that visual arrays are organized into objects at an early point in perceptual analysis. Two plausible, competing theses concerning the nature and development of this capacity appeared to be the thesis that objects are constructed from a structureless visual tableau through activities such as visually guided reaching (e.g. von Helmholtz 1885; Piaget 1954) and the thesis from gestalt psychology that objects are perceived by virtue of a general, unlearned tendency to organize experience into the simplest and most regular configuration (e.g. Koffka

1935). In an attempt to test these theories, Kellman and I investigated young infants' perception of partly hidden objects (Kellman and Spelke 1983). We asked whether infants below the age of visually guided reaching perceive a centre-occluded object as two separate visible fragments or as one unit that is continuous behind its occluder.

Our studies used a habituation of the looking time method. Four-month-old infants were presented repeatedly with an object that was partly hidden by a second object (Fig. 7.1(a)). On each of the series of trials, the objects were presented for as long as an infant looked at them; such presentations were repeated until the infant's looking time declined to half its original level. Then the infants were presented with two non-occluded object displays on alternating trials: a complete object and a broken object with a gap where the occluder had been (Fig. 7.1(b)). The complete object corresponded to the object adults report seeing in the partial occlusion display; the broken object corresponded to the visible areas of the object in the occlusion display. Looking time to these two test displays was measured, on the assumption that infants would generalize habituation to the display corresponding to what they had previously seen and would look longer at the other display (see Kellman and Spelke (1983) and Spelke (1985) for a discussion of these assumptions and of the evidence to support them).

A number of different occlusion displays were presented in different experiments to determine whether, and under what conditions, centre-

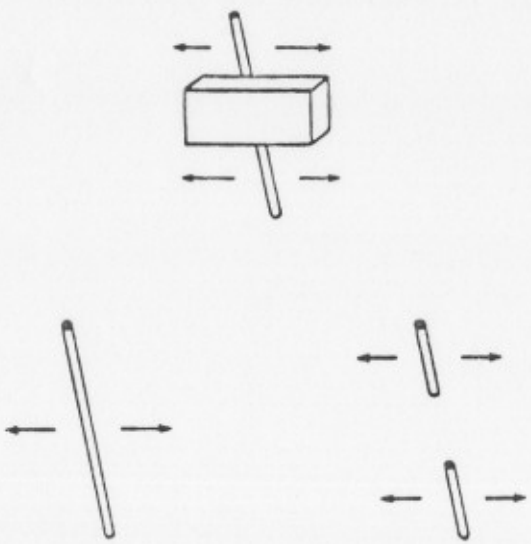

Fig. 7.1 Schematic drawings of the habituation and test displays for an experiment on the perception of the unity of a partly hidden object (from Kellman and Spelke 1983).

occluded objects are perceived as continuous units. These studies provided evidence that infants perceive a partly hidden object as a connected unit if the ends of the object move together behind the occluder (Kellman and Spelke 1983). Any unitary translation of the rod in three-dimensional space leads infants to perceive a continuous object: vertical translation and translation in depth have the same effect as lateral translation (Kellman *et al.* 1986). These findings provided evidence against the constructivist view, and they appeared to support the gestalt thesis. Further findings, however, have called the gestalt analysis into question. Infants do not appear to perceive the continuity of a partly hidden object by analysing the static configurational properties of a display in accord with the gestalt principles of similarity, good continuation, closure, and good form. For example, experiments have provided evidence that infants perceive a connected object just as strongly when they view a moving display that is irregular in its gestalt properties (Fig. 7.2) as when they view a moving display with regular gestalt properties such as that in Fig. 7.1 (Kellman and Spelke 1983). When infants were presented with a stationary object that was regular in form and homogeneous in colour (Fig. 7.3), moreover, their perception appeared to be indeterminate between a connected object and two object fragments: infants dishabituated equally to these test displays (Schmidt and Spelke 1984; also, see Schmidt *et al.* 1986). These findings contrast with the reports of adults who were shown the same displays. Adults' apprehension of centre-occluded objects is affected both by motion and by static gestalt properties (Kellman and Spelke 1983; Schmidt, unpublished thesis, 1985), whereas infants appear to be affected by motion alone.

Similar conclusions follow from research on infants' perception of object boundaries. Infants were presented with two objects in arrangements such as that in Fig. 7.4. Perception of the boundary between the objects was investigated by means of methods assessing object-directed reaching (von Hofsten and Spelke 1985), number detection (Prather and Spelke 1982),

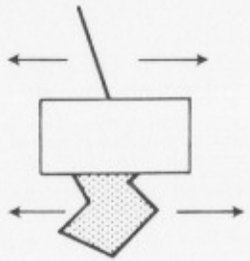

Fig. 7.2 Habituation display for an experiment on perception of the unity of partly hidden moving objects with irregular shapes and colouring (from Kellman and Spelke 1983).

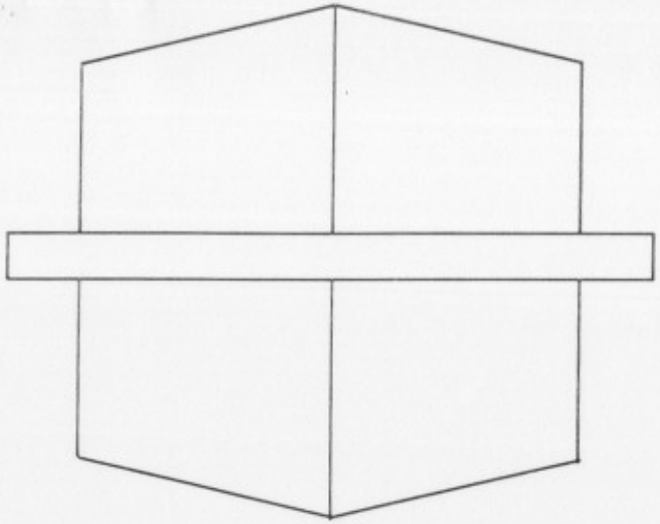

Fig. 7.3 Habituation display for an experiment on perception of the unity of partly hidden stationary objects (from Schmidt and Spelke 1984).

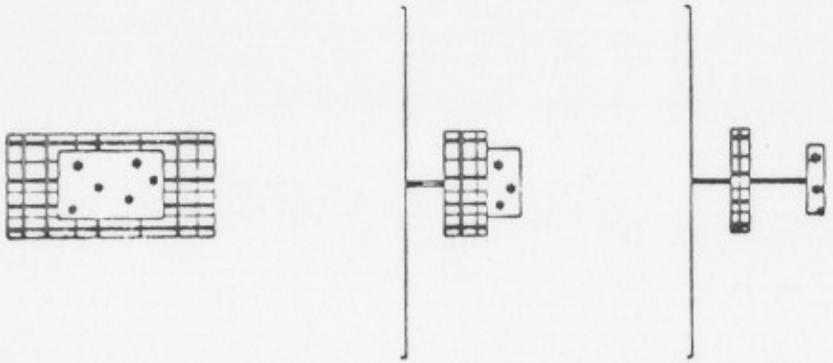

Fig. 7.4 Front and side views of the habituation display for an experiment on perception of the boundaries of adjacent objects (from Kestenbaum *et al.* 1987).

surprise reactions (Spelke *et al.*, unpublished manuscript, 1983), and habituation–dishabituation (Kestenbaum *et al.* 1987). Infants were tested at three to five months of age. All the experiments provided evidence that infants perceive two objects as separate units when (a) either object moves relative to the other, or (b) the objects are stationary and are spatially separated in any dimension, including separation in depth. In contrast, infants do not appear to perceive

object boundaries by forming units that are maximally regular in their gestalt properties. When two stationary objects are adjacent, for example, they are perceived as a single unit even if they differ in colour and texture and if their edges are misaligned. These findings again contrast with those obtained with adults, who perceive object boundaries by detecting not only the motions and the spatial arrangements of surfaces but also their static configurational properties.

To summarize our earlier work, young infants appear to organize the surface layout into units by analysing surface arrangements and surface motions so as to form units that are *cohesive* and *bounded*: connected bodies that move as wholes, independently of other bodies. Infants do not appear to organize the layout into units by analysing the colours and shapes of surfaces so as to form units that are maximally regular in colour, texture, and form. The failure of infants to use gestalt properties is intriguing, because young infants do *detect* these properties of displays. They detect the goodness of a figure, the alignment of a set of edges, and the homogeneity or inhomogeneity of surface colouring (for a review, see Banks and Salapatek 1983). Studies by Schmidt provide evidence that infants detect gestalt properties of the very displays we present in our object perception studies (Schmidt and Spelke 1984). But infants do not *use* these perceivable properties of the surface layout when they organize the layout into objects.

These findings suggest that both constructivist and gestalt accounts of the development of object perception are wrong, but what is wrong with them? Further studies of infants suggest an answer, for they provide evidence that the mechanism by which infants apprehend objects is more central than traditional theories had envisaged. First, the mechanism of object perception appears to perform an analysis of properties of the surface layout as it is perceived; it does not operate directly on patterns of optic, acoustic, or haptic stimulation. Second, the mechanism appears to be amodal, accepting input from different perceptual systems. Third, the mechanism appears to carry infants beyond the world of immediate perception, allowing them to make sense of events in which objects are completely hidden and to predict the future behaviour of those objects. I will describe the evidence for each of these conclusions in turn.

The information for object unity

Evidence that the mechanism for apprehending objects operates on a representation of the perceived layout comes from an experiment by Kellman *et al.* (1987). The experiment investigated whether infants apprehend the unity of a moving, partly hidden object by detecting *proximal* or *distal* motion: patterns of two-dimensional displacement in the immediate optic array or patterns of three-dimensional displacement through the perceived surface

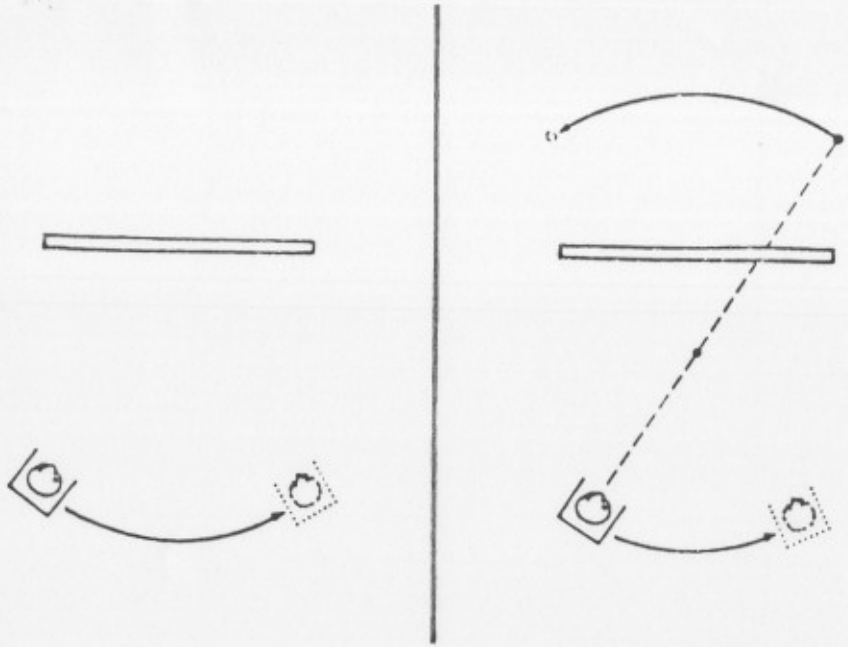

Fig. 7.5 Top view of the experimental situation in the proximal motion condition (left) and the distal motion condition (right) of an experiment on perception of partly occluded objects by a moving observer (from Kellman *et al.* 1987).

layout. To distinguish proximal from distal displacements, infants were presented with a centre-occluded object while they themselves were in motion (Fig. 7.5): they faced a rod and block display while sitting in a chair that moved back and forth in an arc. The rod was stationary in one condition, and thus its image was displaced in the visual field as the baby moved. The rod moved conjointly with the infant in the other condition, 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 by means of the habituation method.

Infants in the proximal motion condition of this experiment showed the same looking patterns as infants in the previous experiments with stationary objects: they looked equally at the complete and broken test rods. This looking pattern provides evidence that the infants did not perceive the rod as complete. In contrast, infants in the distal motion condition showed the same looking patterns as infants in the previous experiments with moving objects:

they generalized habituation to the complete rod and looked longer at the broken rod. This looking preference provides evidence that they perceived the rod as a connected unit. Perceived distal motion, not proximal motion, evidently serves to organize surfaces into objects. The apprehension of objects thus appears to occur more centrally than the perception of space and motion. Infants first perceive the arrangements and motions of surfaces in a three-dimensional layout, and then they group the surfaces they perceive into units that are spatially connected and separately movable.

Apprehending objects by touch

The next studies, conducted with Streri in Paris, investigated whether infants apprehend objects by means of separate, modality-specific mechanisms or by means of a single, more central mechanism (Streri and Spelke 1988). The experiments focused on object perception in the haptic mode, asking whether infants perceive the unity and boundaries of objects under the same conditions when they feel surfaces as when they see them. If object perception depends on modality-specific mechanisms, we reasoned, then objects might well be perceived under different conditions when an infant feels surfaces than when he sees them. If object perception depends on a single amodal mechanism, in contrast, then object perception should follow the same principles in the two input modes.

Four-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. In our first experiments, the rings either could be moved independently or they could only be moved rigidly together. Figure 7.6 depicts the display of rigidly movable objects. Infants were allowed to move the rings at will, and they did so quite actively. (Few infants ever touched the area between the rings; those who did could be eliminated from the analysis without changing the results.) To investigate whether infants perceived the independently movable rings as separate objects and the rigidly movable rings as a single connected object, half the infants were habituated to each haptic display, and then the infants were shown alternating visual displays of connected and separated rings undergoing no distinctive motion. Looking time was measured as in the previous habituation experiments.

In these experiments, habituation to the independently movable rings was followed by greater generalization to the separated display, providing evidence that infants perceived the independently moving rings as distinct objects. In contrast, habituation to the rigidly movable rings was followed by greater generalization to the connected display, providing evidence that infants perceived the commonly moving rings as a single object. Motion therefore appears to specify the unity and boundaries of objects in the haptic mode as it does in the visual mode. Our most recent research suggests,

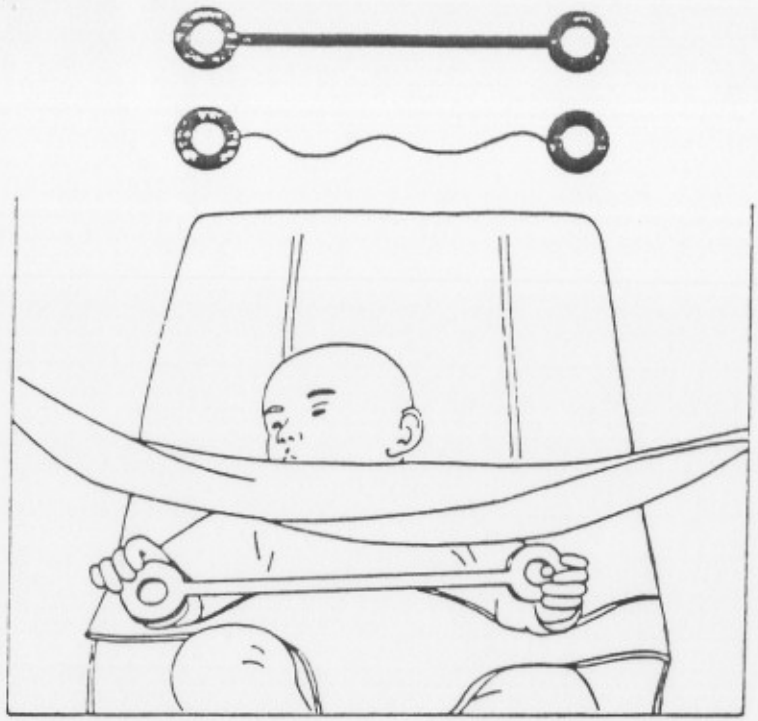

Fig. 7.6 Objects and apparatus for experiments on haptic perception of objects (from Streri and Spelke 1988).

moreover, that gestalt configurational properties fail to influence infants' organization of felt arrays, as they fail for visual arrays (Streri and Spelke, in prep.). Infants perceive the unity of two rigidly movable surfaces that differ in texture, substance, and form just as readily as they perceive the unity of two rigidly movable surfaces of the same texture and substance and of one simple form. These findings provide evidence that objects are perceived under the same conditions whether they are seen or felt. Objects do not appear to be apprehended by separate visual and haptic mechanisms but by a single mechanism that operates on representations arising either through vision or through touch.

Inferring the behaviour of hidden objects

The last experiments investigated whether infants apprehend objects in situations beyond the domain of immediate perception, making inferences about the behaviour of objects that move fully out of view and about the identity or distinctness of objects encountered at different places and times.

The development of knowledge of object persistence and identity has been a subject of intense study ever since the work of Piaget (1954). Most of this research has been taken to provide evidence for dramatic developmental changes in infants' conceptions of objects: it is generally believed either that humans begin life with no conception of object persistence and identity (e.g. Piaget 1954; Harris 1983) or that humans begin with conceptions of objects that differ radically from the conceptions of adults (e.g. Bower 1982). I am led to question these conclusions, however, because of one problematic feature of the research on which they are based. Infants' conceptions of objects are usually studied by observing infants' co-ordinated search for objects: their patterns of tracking objects visually or retrieving objects manually. Developmental changes in such activities need not imply developmental changes in conceptions of objects, since the capacity for co-ordinated action may itself undergo development. Curiously, Piaget's studies of sensori-motor development provide strong evidence that action capacities do grow and change over infancy, and that the actions required by search tasks are themselves beyond the capacities of young infants (Piaget 1952). To investigate the development of infants' conceptions of objects, therefore, it is necessary to focus on behaviours that are within the young infant's repertoire. Our own experiments have begun to investigate young infants' conceptions of object persistence and object identity by means of preferential looking methods.

Our first experiments focused on five-month-old infants' apprehension of objects as persisting over full occlusion (Baillargéon *et al.* 1985). The critical events in this study involved a stationary block behind a rotating screen. As the screen rotated upward, it hid the object completely. Then the screen either rotated until it reached the place the block had occupied (Fig. 7.7(a)) or it rotated 180° through that place (Fig. 7.7(b)). To adults, the first of these events is expected and the second is surprising, since one object cannot pass

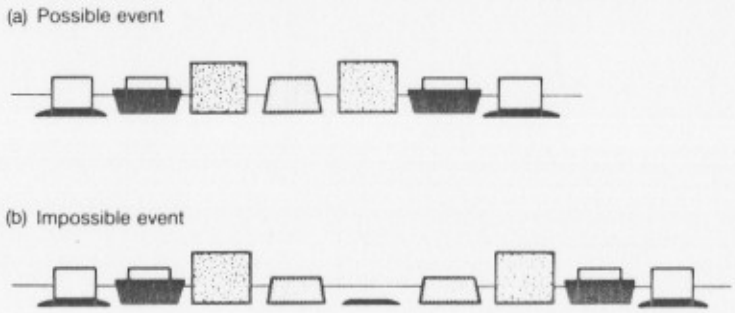

Fig. 7.7 Test displays for an experiment on knowledge of object persistence (from Baillargéon *et al.* 1985).

through a place occupied by another object. To investigate how infants conceive these events, the events were embedded in an experiment in which infants were first habituated to the screen rotating 180° with no block present. Then infants were tested with the block and the screen undergoing the novel but possible rotation and the familiar but impossible rotation. Infants looked longer at the impossible rotation. With appropriate controls (see Baillargéon *et al.* 1985), this experiment provided evidence that infants represent the continuous existence of the block behind the screen.

Further research by Baillargéon (in press *a*) provided evidence that even three- and four-month-old infants perceive objects as persisting over full occlusion. In studies with older infants, she has found that infants represent not only the existence of a hidden object but also its motion in relation to other hidden objects (Baillargéon 1986), its orientation (Baillargéon, in press *b*), and its height (Baillargéon, in prep.). Her experiments provide evidence that infants conceive of objects both as persisting and as substantial: objects exist continuously and move only through unoccupied space.

Current studies with Macomber and Keil provide further evidence that infants conceive of objects as persisting and substantial (Macomber *et al.*, in prep.). In one study, four-month-old infants were habituated to an event in which an object was dropped behind a screen on an open stage, and then the screen was lifted to reveal the object on the ground of the stage. Infants then were tested with events in which a table was placed on the stage in the object's path of motion, the object was again dropped behind the screen, and the screen was lifted to reveal the object either in a new position on top of the table or in its old position below the table (Fig. 7.8). The infants looked longer when the object was in its old position beneath the table, in accord with the principle that objects cannot move through solid surfaces. This finding converges with the findings of Baillargéon, providing evidence that infants, like adults, represent hidden objects and make inferences about the behaviour of such objects in accord with the notion that objects are substantial.

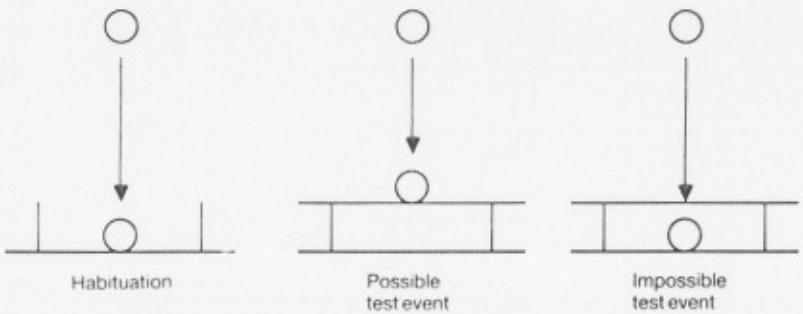

Fig. 7.8 Habituation and test displays for an experiment on knowledge of object substance (from Macomber *et al.*, in prep.).

A further study by Macomber suggests a limit to young infants' physical knowledge: infants below five months do not appear to conceive of objects as subject to gravity. Four-month-old infants were habituated to an event in which an object fell behind a screen and then was revealed at rest upon a table: the possible test event of the first experiment. Then infants were tested with events in which the table was removed and the object either came to rest in a new position on the floor of the display or in its former position, now unsupported in mid-air (Fig. 7.9). Adults report that the latter event is surprising, since the object stops moving without any visible support. Infants, in contrast, showed little interest in this event: they generalized habituation to the unsupported object and looked longer at the supported object in the new position. Young infants may fail to predict where and how objects will move in accord with the notions that objects are subject to gravity and must be stably supported.

Consider, finally, infants' apprehension of the identity of objects that move in and out of view. One way of apprehending object identity, much discussed in philosophy, is to trace the apparent continuity or discontinuity of object motion (e.g. Hirsch 1982). For adults, physical objects must move on continuous paths; they cannot jump from one place to another. Our first experiments investigated whether four-month-old infants apprehend the identity or distinctness of objects over occlusion in accord with this principle (Spelke and Kestenbaum 1986). Following research by Moore *et al.* (1978), infants were presented with events involving two screens, as in Fig. 7.10. In one event, a single object moved continuously across the display, disappearing behind each screen in turn. The second event was identical 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. In both events, the motions were slow enough that adults do not report that they 'perceive' a continuously persisting object, as in the case of apparent

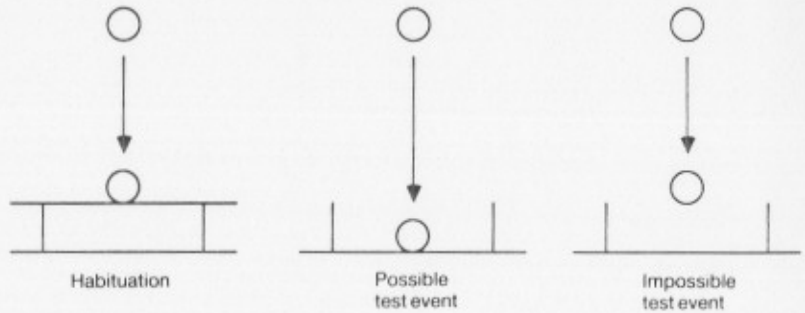

Fig. 7.9 Habituation and test displays for an experiment on knowledge of gravity (from Macomber *et al.*, in prep.).

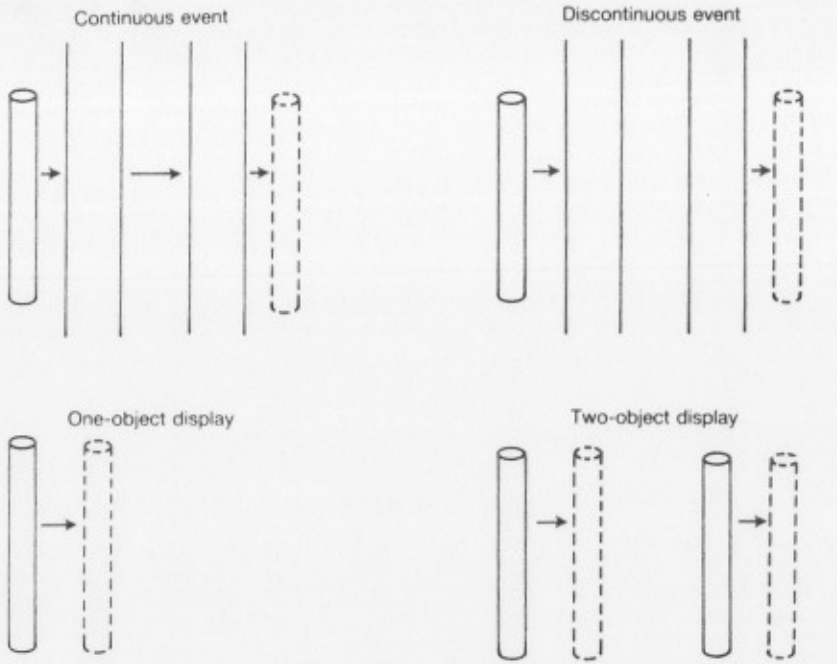

Fig. 7.10 Habituation and test displays for experiments on infants' knowledge of spatio-temporal continuity (from Spelke and Kestenbaum 1986).

motion or amodal completion (Michotte 1963). Nevertheless, adults judge that the first event involves one object and the second event involves two objects (Spelke *et al.*, in prep.). These judgements follow from the notion that objects move on continuous paths.

In three experiments, separate groups of 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 no distinctive motion. The infants who were habituated to the continuous event generalized more to the one-object display, providing evidence that they perceived the continuous event as involving one object. In contrast, the infants who were habituated to the discontinuous event generalized more to the two-object display, providing evidence that they perceived the discontinuous event as involving two objects. Infants appear to apprehend the identity of objects by analysing the apparent continuity or discontinuity of paths of motion, in accord with the principle that objects move on spatio temporally continuous paths.

Our last experiments suggested that infants fail to apprehend the persisting identity of objects under one set of conditions that are effective for adults. If an object moves in and out of view on alternate sides of one wide screen, and if its

occlusion time is appropriate to its visible speed of motion, adults will judge that it is a single, persisting body. If the occlusion time is much shorter, adults are apt to judge that two objects participated in the event, one appearing on each side of the screen. In our research, infants were not affected by an object's apparent velocity (Spelke *et al.*, in prep.). Their perception of the identity or distinctness of objects appeared to be indeterminate and, equally so, whether or not an object's occlusion time was appropriate to its speed of motion. Infants evidently apprehend object identity in accord with the principle that objects move on continuous paths but not the principle that objects move at constant or gradually changing speeds.

Object perception and the object concept

To summarize, all these experiments provide evidence that infants can sometimes apprehend the unity, the boundaries, the persistence, and the identity of objects. Objects are apprehended by a relatively central mechanism that takes as input the layout as it is perceived, whatever the sensory mode by which it is perceived, and that organizes events in ways that extend beyond the immediately perceivable world in space and time. This mechanism organizes the layout into bodies with at least four properties: *cohesion*, *boundaries*, *substance*, and *spatio–temporal continuity*. Infants are able to find such bodies, because these properties limit were surfaces stand and how they move with respect to one another. The surfaces of a cohesive body must be connected and they must remain connected over the body's free motions; the surfaces of a bounded body must be distinct from the surfaces around them and they must move independently of their surroundings; the surfaces of a substantial body must move through unoccupied space; and the surfaces of a spatio temporally continuous body must move on connected paths. Infants apprehend objects by analysing the arrangements and the motions of surfaces, I suggest, because they conceive the physical world as populated with bodies whose properties constrain surface arrangements and motions.

Infants may fail to apprehend objects by analysing gestalt relationships, support relationships, or velocity relationships, because they do not conceive the physical world as populated with bodies whose properties constrain such relationships. The relationships are perceived, and they may be used by other central mechanisms for other purposes. Object form, for example, may be used by an early developing mechanism for representing space and guiding navigation, as Cheng and Gallistel (1984; also see Cheng 1986) and Landau (see Landau *et al.* 1984) have proposed. Object support and object velocity may be used to guide early object-directed reaching (Bresson and de Schönen 1976–7; von Hofsten 1979; Piaget 1954). These relationships will not be used for purposes of apprehending objects, however, until children learn that objects tend to be regular in substance and form, that objects are subject to gravity, and that objects tend to move at gradually changing speeds.

I suggest that the infant's mechanism for apprehending objects is a mechanism of thought: an initial *theory* of the physical world whose four principles jointly define an initial *object concept*. This suggestion is motivated not only by evidence of the centrality of the mechanism for apprehending objects, but also by a consideration of the principles governing its operation. The principles of cohesion, boundedness, substance, and spatio-temporal continuity appear to stand at the centre of adults' intuitive conceptions of the physical world and its behaviour: our deepest conceptions of objects appear to be the notions that they are internally connected and distinct from one another, that they occupy space, and that they exist and move continuously (for further discussion, see Spelke 1983, 1987). These conceptions are so central to human thinking about the physical world that their uniformity sometimes goes unremarked. In studies of intuitive physical thought, for example, much attention is paid to the idiosyncratic and error-ridden predictions adults sometimes make about the motions of objects (e.g. McCloskey 1983). It is rarely noted, however, that adults predict with near uniformity that objects will move as cohesive wholes on connected paths through unoccupied space. This conception, at least, is clear and central to our thinking; it appears to have guided our thinking since early infancy.

The centrality, for adults, of the initial conception of objects suggests that the spontaneous development of physical knowledge is a process of *theory enrichment*, in which an unchanging, core conception of the physical world comes to be surrounded by a periphery of further notions. It is not difficult to see, in outline, how theory enrichment could occur. If an initial theory of the physical world allows children to single out objects, then children will be able to acquire further knowledge about objects by following them through time and observing their behaviour. The initial theory will perpetuate itself over the learning process, because the entities the child learns about will be just the entities that his initial theory has specified. Theory enrichment seems likely to occur whenever humans acquire knowledge spontaneously in an innately structured domain. In domains where humans have no initial theory, systematic knowledge may not develop spontaneously at all.

Language and conceptual development

In this context, one may consider the possible role of language in the development of physical knowledge. Our research provides evidence, counter to the views of Quine (1960) and others, that the organization of the world into objects precedes the development of language and thus does not depend upon it. I suspect, moreover, that language plays no important role in the spontaneous elaboration of physical knowledge. To learn that objects tend to move at smooth speeds, for example, one need only observe objects and their motions; one need not articulate the principles of one's theory or communi-

cate with others about it. It is possible, nevertheless, that language influences conceptual development at certain critical times, when the child or adult finds himself on the edge of a domain of entities that his initial theories do not single out and cannot describe. When we recognize the need to reorganize the physical world from a realm of objects into a realm of matter, for example (see Smith *et al.* 1985), or from a realm that is three-dimensional into a realm of higher dimensionality, we may do so by modifying our theories explicitly or by bringing to bear theories of other domains. Communicating with others who have made this leap, and/or articulating the principles of the new theory to be applied, may play critical roles in this process of conceptual change.

The distinction between development as the spontaneous enrichment of theories and development as the laboured reorganization of theories may point to a general role of language in thought and to a general difference between human adults, on the one hand, and human infants and non-human species, on the other. As adults, we may transcend current theories of the world when we reach their limits, and this ability may be unique to us. I am struck, nevertheless, by what I think is a profound similarity between adults and infants, and probably between humans and many other animals. Infants, like adults, appear to conceive the world in terms of physical bodies and to use this conception to support inferences and predictions about physical events. In content, the infant's conception of the physical world appears to constitute the core of our physical conception as adults. This conception may first reveal itself when infants apprehend objects and make sense of their behaviour in the perceived spatial layout.

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