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Modality-specific and amodal aspects of object perception in infancy: The case of active touch

Arlette Streri*[,a], Elizabeth Spelke[b], E. Rameix[a]

[a]*Laboratoire de Psychologie du développement et de l'education de l'enfant (LAPSYDEE), Université de Paris V, 28 rue Serpente, 75005 Paris, France*
[b]*Department of Psychology, Cornell University, 248 Uris Hall, Ithaca, NY 14853, USA*

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Abstract

Three experiments investigated 4.5-month-old infants' perception of the unity and boundaries of haptically presented objects. When infants actively explored the two handles of an unseen object assembly, perception of the unity of the assembly depended on the handles' motion. Infants perceived a single, connected object if the handles moved rigidly together, and they perceived two distinct objects if the handles underwent relative vertical or horizontal motion. When infants passively explored the same object assembly undergoing the same motions, object perception appeared to be indeterminate. The findings of the active motion experiments accord with the findings of studies of visual object perception and suggest that object perception depends on amodal processes, operating on representations of either seen or felt surface motions. The findings of the passive motion experiments nevertheless suggest a difference between visual and haptic perception: for infants as for adults, haptic perception is enhanced by the active production of surface motion.

Introduction

Although the processes by which perceivers organize the surrounding surface layout into unitary, bounded objects are fundamental to perception, cognition

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*Corresponding author.

and learning, it is widely conceded that these processes are poorly understood (e.g., Gallistel, 1990; Hochberg, 1974; Marr, 1982). For example, it is not known whether representations of visible objects are constructed by early visual processes that operate on a representation of intensity changes or elementary features in the optic array, or by later processes that operate on a representation of surface depth and three-dimensional motion (for contrasting views, see Marr, 1982; Witkin & Tenenbaum, 1983). Furthermore, it is not known whether the processes of object perception are modality-specific or amodal: do perceivers have separate visual mechanisms and haptic mechanisms for parsing the surface layout into objects, or does a single mechanism accomplish this task by operating on input from either perceptual mode? The present research attempts to address the second question, and to approach the first question, by investigating object perception in infancy.

Studies of early development may shed light on processes of object perception in two ways. First, young infants appear to perceive objects under some, but not all, of the conditions that are effective for adults (see Spelke, 1990; Streri, 1993; and below). It is reasonable to assume that the perceptual capacities that are common to infants and adults depend on common underlying mechanisms. Like studies in cognitive neuropsychology, therefore, studies of early development may serve to delineate aspects of the organization of mature object perception by investigating the detailed characteristics of infants' capacities. Second, young infants are likely to know little about the appearance and behavior of objects of particular kinds: presented with natural settings, young infants are not apt to recognize objects such as a lamp or telephone and scenes such as a cluttered desk or kitchen. Studies of young infants therefore may reveal the operation of basic perceptual processes before those processes are overlaid by a wealth of specific knowledge.

In the present research, we ask whether the processes of object perception that are mature and functional in early infancy depend on separate modality-specific mechanisms or on a single, amodal mechanism. This research is based on the findings of studies of visual object perception in infancy, reviewed below. It investigates whether $4\frac{1}{2}$-month-old infants perceive haptically presented objects under all, and only, the conditions that lead to effective perception of visually presented objects. To the extent that object perception depends on amodal mechanisms, then parallel results regarding infants' perception of object boundaries should be obtained in the visual and the haptic modes, even when infants are tested under conditions in which visual and haptic stimulation are not equally informative about objects. To the extent that object perception depends on modality-specific mechanisms, in contrast, infants might perceive objects differently in the two modes, especially when the same patterns of visual and haptic stimulation provide different information about object boundaries and give rise to different perceptions of objects in adults.

Visual perception of objects in infancy

At 3–5 months of age, perception of visually presented objects depends primarily on an analysis of surface motion. Infants perceive two adjacent objects as a single unit if the objects undergo a rigid horizontal motion (Hofsten & Spelke, 1985; Spelke, Hofsten, & Kestenbaum, 1989; Fig. 1a, b), and they perceive the two visible ends of a center-occluded object as one connected body if the ends move rigidly together either horizontally, vertically, or in depth (Kellman, Gleitman, & Spelke, 1987; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986). Infants also perceive the distinctness of two adjacent objects if the objects undergo different rigid motions (Hofsten & Spelke, 1985; Spelke et al., 1989; Fig. 1c, d). Relative motion in a single direction is sufficient to specify object boundaries both to infants and to adults: Two objects that undergo relative horizontal motion are perceived as distinct, even if the objects maintain constant spatial relations both vertically and in depth.

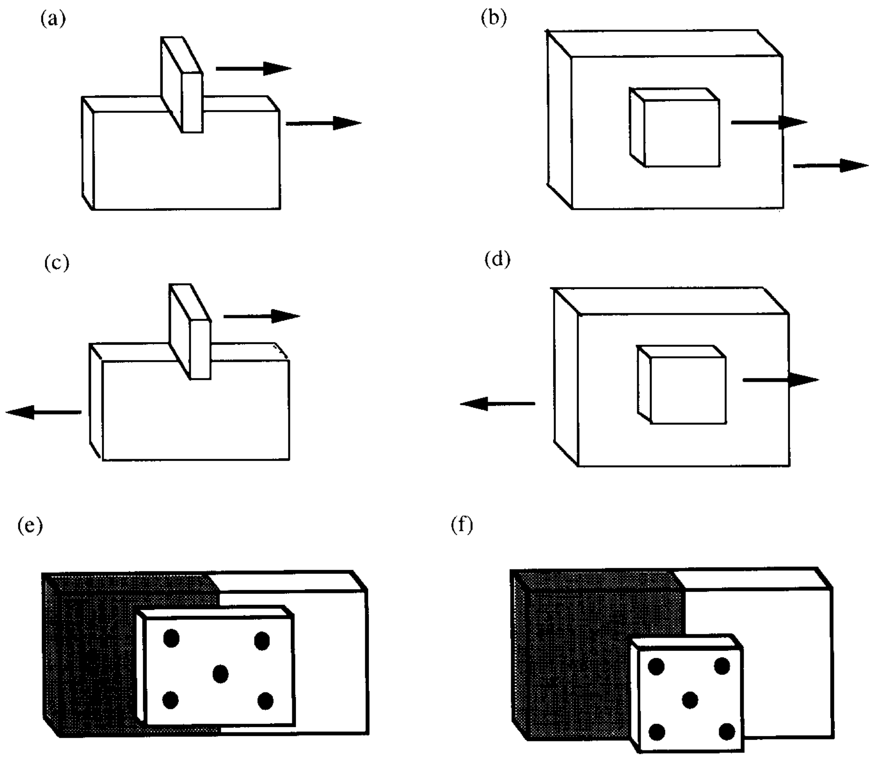

Figure 1. *Schematic depiction of displays from experiments on infants' perception of the boundaries of visible objects. Arrows indicate the path of object motion. After Spelke et al. (1989) (a, c), Hofsten and Spelke (1985) (b, d), and Kestenbaum et al. (1987) (e, f).*

In contrast, 3–5-month-old infants do not appear to perceive the unity or boundaries of visible objects by analyzing properties of the layout such as surface color, texture, or orientation. Unlike adults, infants perceive the unity of a rigidly moving, center-occluded object just as strongly when the visible ends of the object differ in shape and color, have misaligned edges, and comprise no simple form, as when the ends of the object are homogeneous in color and texture and comprise a smooth and simple shape (Kellman & Spelke, 1983; see also Craton & Baillargeon, 1991; Schmidt, 1985). Furthermore, infants perceive two stationary, adjacent objects as a single unit, even when the objects differ in color, texture, and shape and have misaligned edges (Kestenbaum, Termine, & Spelke, 1987; Fig. 1e, f; see also Hofsten & Spelke, 1985; Spelke et al., 1989). Infants therefore perceive object unity and boundaries by detecting some, but not all, of the information that specifies objects for adults.

Haptic perception of objects in infancy

Presented with a tangible array of surfaces, infants also perceive unitary and bounded objects by detecting the common and relative motions of surfaces. Because these abilities form the background for the present research, the experiments that document them will be described in some detail (see also Streri, 1993).

Streri and Spelke (1988) presented $4\frac{1}{2}$-month-old infants with two rings, one in each hand, underneath a bib that blocked their view of the rings and of their own hands and arms. In one condition, the rings were rigidly connected by a bar. Although the bar was neither seen nor felt directly, it constrained the rings to move rigidly together (Fig. 2a). In the other condition, the rings were connected by a long and very flexible elastic band that allowed infants to move them independently (Fig. 2b).

On a series of habituation trials, infants explored a ring assembly at will, producing one rigid motion in the first condition and two independent motions in the second condition. After habituation, the rings were removed and infants were shown two visual test displays, one presenting the two rings with a rigidly connected center and the other presenting the two rings separated by a gap. Looking times to the displays were compared with each other and with the looking times shown by infants in a baseline condition, who had received no haptic habituation experience. The looking preferences in the two experimental conditions differed markedly. Comparing each condition to baseline, the infants habituated to the rigidly movable rings showed a preference for the separated rings, whereas those habituated to the independently movable rings showed a preference for the connected rings. These findings provided evidence that infants

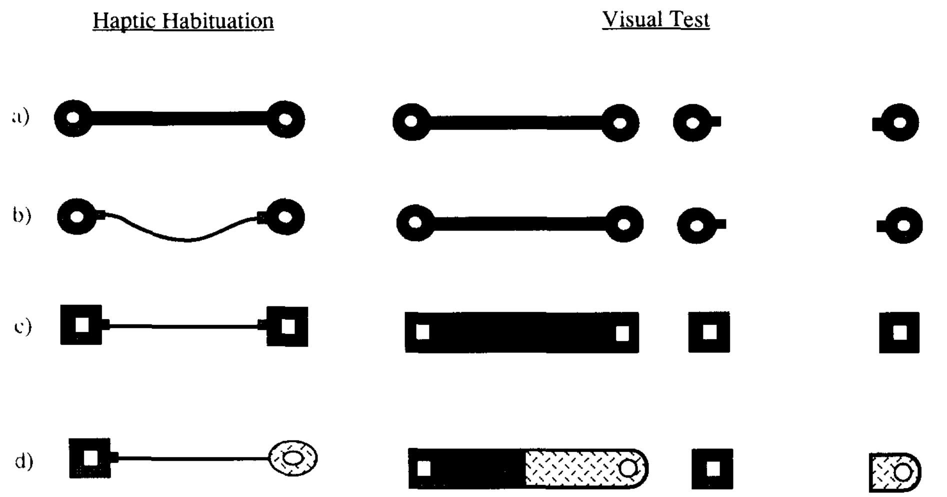

Figure 2. *Schematic depiction of displays from experiments on infants' perception of the boundaries of haptically presented objects. After Streri and Spelke (1988) (a, b) and Streri and Spelke (1989) (c, d).*

perceived the rigidly movable rings as one connected object and the independently movable rings as two separated objects.

Subsequent experiments investigated whether infants' perception of the unity and boundaries of haptically presented objects was affected by the objects' static configurational properties (Streri & Spelke, 1989). Infants aged $4\frac{1}{2}$ months were presented with two rigidly movable rings that were either round or square, hard or soft, rough or smooth, and heavy or light. In one condition, the two rings were the same on all four dimensions and could be combined to form an object of a simple shape (e.g. Fig. 2c); in the other condition, the two rings differed on all four dimensions and could not be combined into a simple shape (Fig. 2d). After habituation to a ring assembly, infants were presented with alternating visual displays of connected and separated rings. Infants in both conditions showed equally large and reliable preferences for the separated rings, providing evidence that they perceived both haptic ring assemblies as connected. In contrast to adults, who were also studied, infants' perception was unaffected by the objects' static configurational properties.

The concordance between the findings of studies of visual and of haptic object perception is consistent with the thesis that a single, amodal mechanism underlies object perception in infancy. Nevertheless, Kellman (1988) has suggested an alternative interpretation of these findings. The motion relationships that have been found to specify object unity and boundaries for infants may provide the most useful and reliable visual and haptic information about objects, for perceivers at any age. Whereas seen or felt objects are not always regular in shape and uniform in texture, objects almost always move as wholes, independently from their surroundings. If patterns of common and independent motion are maximally informative about objects, however, then separate visual and haptic mechanisms for perceiving objects may have become attuned to these surface motions, either through learning during the first months of life or through convergent evolution.

The present research attempts to distinguish between the amodal mechanism thesis and Kellman's (1988) alternative thesis, by investigating infant's perception of objects from patterns of motion that are *not* equally informative in the visual and haptic modes and that give rise to different perceptions, in those two modes, in adults. We focus on two differences between the motion information that specifies the boundaries of visible and tangible objects. First, certain patterns of constrained relative motion appear to specify that two surfaces lie on separate objects when the surfaces are visible, but that two surfaces lie on the same object when the surfaces are tangible. Second, motion that is witnessed but not produced by the perceiver appears to be more informative about objects that are seen than about objects that are felt.

Modality specificity in object perception

As noted above, infants perceive two visible objects as distinct units if the objects undergo relative motion in one direction alone (e.g., Hofsten & Spelke, 1985, Fig. 1d). Informal studies with these displays, and more systematic studies with related displays (see Kellman & Spelke, 1983; Kestenbaum et al., 1987), indicate that adults perceive the separateness of such objects as well. In contrast, consider a haptic assembly consisting of two handles that could undergo relative motion in one direction alone: for example, handles that slide with respect to one another only horizontally (Fig. 3a) or vertically (Fig. 3b). A perceiver who manipulated this assembly would discover that the motions of the two handles are constrained: every vertical displacement of one handle in Figure 3a, for example, is accompanied by a corresponding displacement of the other handle. This constraint should specify that the handles are connected in some (perhaps complex) way. The handles could not be fully separate objects, because such objects would move independently in *all* directions.

To our knowledge, adults' perception of objects such as those in Fig. 3(a, b) has not been studies (that is the purpose of Experiment 1). Related experiments suggest, however, that adults would not perceive such objects as fully separated bodies. In experiments by Lederman and Klatzky (1987), subjects held unfamiliar objects with a part that could not be detached but that could undergo constrained relative motion. The subjects explored the objects by displacing that part relative to the rest of the object. In subsequent research in which the objects were familiar, this exploratory pattern did not lead adults to perceive two distinct objects; on the contrary, it facilitated recognition of a single object (Lederman & Klatzky, 1990). These findings suggest that adults, presented haptically with an assembly whose parts underwent constrained relative motion, would perceive the assembly as one connected body. Adults therefore would perceive certain assemblies differently in the visual and the haptic modes.

The likely difference between adults' visual and haptic perception of displays with constrained relative motion suggests that modality-specific processes influence adults' perception of objects. It is not clear, however, whether the most fundamental processes of object perception are modality specific. Adults may perceive complexly moving objects differently in the visual and haptic modes because basic, amodal processes of object perception have been supplemented by specialized knowledge of the structure and behavior of complexly moving objects, such as drawers or trombones. The modality-specific or amodal character of the basic processes of object perception might be revealed more clearly through research with infants.

The present experiments investigated adults' and infants' perception of haptically presented assemblies composed of two handles that underwent relative horizontal or vertical motion while maintaining a constant spatial relationship along the other two axes. Adults were expected to perceive each assembly as one connected object. If the basic processes of object perception are modality-specific, then infants either should perceive each of the assemblies as a connected body (if the processes underlying adults' perception of these assemblies have developed by 4 months) or their perception should be indeterminate (if the relevant processes develop later in childhood). In contrast, if object perception depends on a single amodal process, then infants should perceive each of the relative motion assemblies as two distinct and fully unconnected objects, in contrast to the perceptions of adults and in accord with infants' perception of objects in the visual mode (Hofsten & Spelke, 1985; Spelke et al., 1989).

The second difference between visual and haptic object perception concerns the role of the perceiver's own activity in the perception of objects and their properties. In the visual mode, both adults and infants perceive objects and their motions without acting on objects to produce their motions. Perceivers cannot use vision to produce object motion but only to perceive motions that are produced by the perceiver's haptic system or by other agents. In contrast, research with adults suggests that self-produced motion is critical to haptic perception (Gibson, 1966; Lederman & Klatzky, 1987; see also Hatwell, 1986; Held & Hein, 1958). Adults sometimes are not able to perceive objects whose motions are felt passively. For example, Gibson (1962) allowed subjects to feel each of a set of cookie cutters of different shapes under two conditions. In one condition, the subjects explored each shape actively and at will; in the other condition, an experimenter pressed each shape into the subjects' motionless palm. Perception of the objects' shape was markedly reduced in the latter condition (see also Lederman & Klatzky, 1987). In contrast to visual perception, adults' haptic perception suffers under conditions in which perceivers cannot interact with the objects to be perceived.[1]

The present experiments accordingly compared adults' and infants' haptic perception of objects whose motions were produced by active manipulation with their perception of objects whose motions were produced by an experimenter. Adults were expected to perceive the boundaries of objects more clearly under conditions of active exploration. If early-developing abilities to perceive objects depend on modality-specific processes, then both infants and adults might perceive the object motions more effectively with their own actions are the source of the motions. If these abilities depend on amodal processes, then infants might perceive the same object boundaries under conditions of self-produced and experimenter-produced motion.

EXPERIMENT 1

The first experiment focused on adults' perception of the haptic assemblies to be presented to infants. Subjects were presented haptically with three object assemblies, each consisting of two handles. In two of the assemblies, the handles could undergo constrained relative motion: they could be pulled apart and pushed together horizontally (Fig. 3a) or vertically (Fig. 3b). As in the studies of visual object perception by Hofsten and Spelke (1985) and Spelke et al. (1989), these handles underwent relative motion only along one axis: for example, the handles that could be moved horizontally maintained a constant spatial relationship both vertically and in depth. In the third assembly, the handles were rigidly connected and underwent only common motion (Fig. 3c). Each subject explored each of the three assemblies under a cloth cover. The subject received one sequence of presentations in which he or she moved each assembly actively and one sequence of presentations in which he or she held each assembly passively while it was moved by the experimenter. For each assembly, the subject judged (a) whether the two handles were connected to one another or not connected, and (b) whether the two handles comprised one object or two objects.

[1]We do not intend that visual perception is passive; on the contrary, visual perception depends on active exploration by a mobile perceiver (Gibson, 1966, 1979). Despite the active nature of visual exploration, however, both adults and infants can perceive objects that move independently of themselves. In this respect, visual and haptic perception inherently differ. (Hatwell, 1986, discusses some consequences of this difference.)

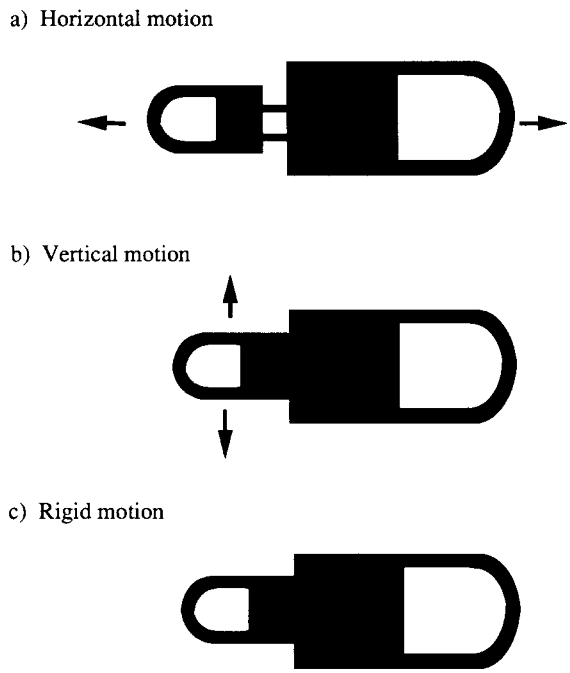

Figure 3. *Schematic depiction of the displays for Experiment 1.*

Methods

Subjects

Participants were 7 men and 5 women ranging in age from 16 to 28 years ($M = 20$ years), who were either students or employees at Cornell University. Three additional subjects were eliminated from the experiment because of failure to produce the relevant object motions (see below).

Displays and apparatus

Each haptic assembly consisted of two wooden handles of unequal size, joined in the center. The smaller handle measured 10×5.5 cm, and the larger handle measured 20×9.5 cm. In the horizontal motion assembly, the handles were joined by brass rods and string, and they could be pushed together and pulled apart by a horizontal sliding motion for a total distance of 5.5 cm. In the vertical motion assembly, the handles were connected by a metal tongue-in-groove arrangement that permitted the small handle to slide vertically between the bottom and the top of the larger handle for a distance of 4 cm. In the rigid motion assembly, the two handles were rigidly attached and underwent no relative motion. All three assemblies moved silently. Each subject sat in an office chair facing a wall of white shelves 1 m away. A cloth, tied around the subject's neck at one end and attached to a shelf at the subject's eye level at the other end, blocked the subject's view of his or her own body and of the displays. One experimenter sat next to the subject, presented all the assemblies, and asked all the questions. A second experimenter sat beneath the cloth, monitored the subject's hand motions, and recorded all the subject's responses.

Design

Each subject received 6 test trials. The three assemblies were presented in a different latinized order in each of two sequences: an active motion sequence and a passive motion sequence. The order of the two sequences was counterbalanced across subjects.

Procedure

Before the experiment, a subject was told she would be asked questions about a series of displays that were used in studies of infant perception. For the active motion sequence, she was told that she would be given a display to hold with both hands, and that she could move the display however she liked, provided that she did not move it into view, press it against the cloth or against her own body, or touch parts of the display that were not given to her initially. An assembly was placed in the subject's hands, and the first experimenter placed her hands over the subject's hands and produced the relevant motion for about 3 s. Then the experimenter released the assembly and the subject moved it at will for about 10 s. The second experimenter monitored the subject's exploration; the subject was eliminated from the experiment if the experimenter noted that she did not produce the relevant motion. For the passive motion sequence, the subject was told to relax her hands on the display and to allow the experimenter to move it for her. An assembly was placed in the subject's hands, and the first experimenter grasped the inner edges of the two handles, without touching the subject's hands, and produced the relevant motions for about 10 s.

After feeling an assembly, the subject was first asked a question about its connectedness: "Does what you are holding in your left hand feel connected to what you are holding in your right hand or not?" Then she was asked about its unity: "Tell me whether what you're holding feels like one object or two objects to you?" After answering each question, the subject rated the strength of her impression of object connectedness and object unity on a 7-point scale.

Analyses

Each subject's ratings were transformed to a single scale from -7 (strong impression of unconnected handles/two objects) to $+7$ (strong impression of connected handles/one object). Ratings for each question and each assembly were compared to the neutral value of 0 by two-tailed t tests. Ratings for different assemblies were compared to each other by a 3 (display: vertical vs. horizontal vs. rigid motion) $\times$ 2 (motion: active vs. passive) analysis of variance with the last two factors within subjects.

Results

Figure 4 (top) presents the mean connectedness ratings for the three assemblies under the active and the passive motion conditions. Each assembly was rated as connected by a majority of the subjects; these ratings differed from neutrality for all three assemblies in the active motion condition, all ts > 60, $p < .001$, and all three assemblies in the passive motion condition, all ts > 2.50, $p < .05$. The analysis of variance revealed significant main effects of motion, $F(1, 11) = 8.50$, $p < .02$, and display, $F(2, 22) = 4.25$, $p < .05$, and a significant motion by display interaction, $F(2, 22) = 3.88$, $p < .05$. Adults' connectedness ratings were higher for actively than for passively moved objects, they were highest for the rigid assembly and lowest for the vertical motion assembly, and differences in ratings for the different assemblies were greater for the passive motion condition, possibly because of a ceiling effect in the active motion condition.

Figure 4 (bottom) presents the mean ratings of object unity. Each assembly was judged to consist of one object by a majority of the subjects. In the active motion condition, these judgments differed from neutrality for the rigid assembly (s.d. $= 0$) and for the horizontal motion assembly, $t = 2.69$, $p < .025$, but not for the vertical motion assembly, $t = 1.77$, $p > .10$. In the passive motion condition, the judgments differed from neutrality for the rigid assembly, $t = 37.62$, $p < .001$, but not for the horizontal or vertical motion assemblies, $t = 1.54$ and $t < 1$, respectively. The only significant effects in the analysis of variance were the main effects of motion, $F(1, 11) = 8.52$, $p < .02$, and display, $F(2, 22) = 6.37$, $p < .01$. Judgments of unity were stronger after active exploration, and they were strongest for the rigid motion display and weakest for the vertical motion display.

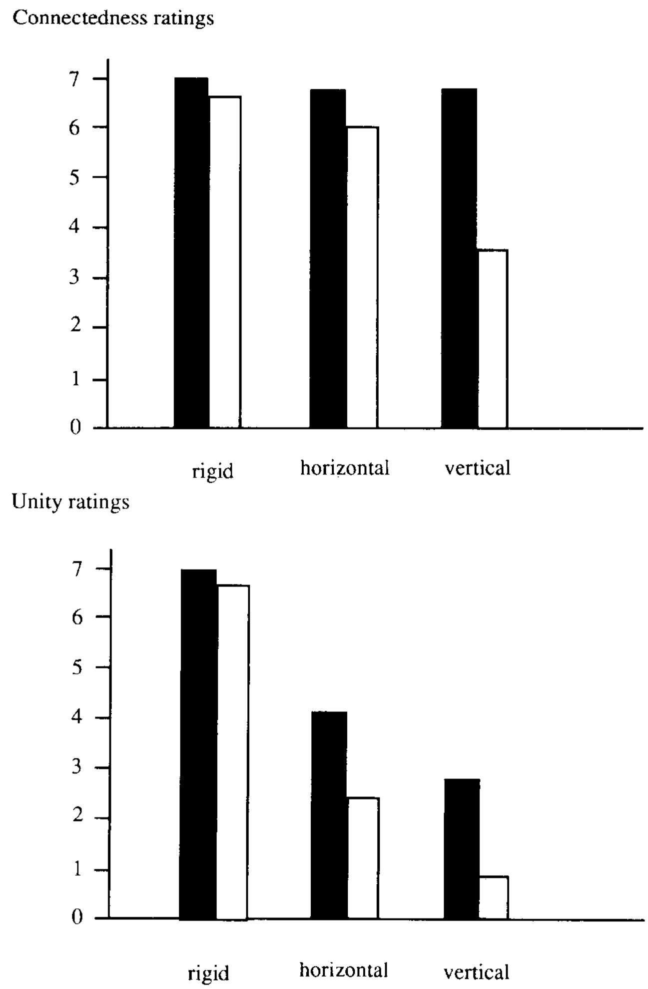

Figure 4. *Adults' mean judgments of the connectedness and the unity of the displays in Fig. 3. presented under conditions of active (■) and passive (□) motion.*

Discussion

This experiment yielded three principal findings. First, adults tended to perceive each relative motion assembly as a single connected object, especially under conditions of active exploration. This finding accords with the findings of Lederman and Klatzky (1990) using a different task and familiar objects. Second, adults' perception of the connectedness and the unity of the haptically presented objects was influenced reliably by the objects' motion. Although adults tended to perceive all the assemblies as connected and unitary objects, this perception was stronger for the rigid assembly than for the relative motion assemblies. Third, adults' perception of object unity was stronger whey they actively produced the objects' motions than when they experienced object motions passively.

Most importantly, Experiment 1 provides evidence that adults perceive objects undergoing limited relative motion differently in the visual and haptic modes. Although two visible objects are perceived as distinct if they undergo relative motion in only one direction, two tangible objects are not. We now ask how infants perceive objects that undergo limited relative motion, under conditions of active haptic exploration.

EXPERIMENT 2

The infants in the two principal conditions of Experiment 2 were familiarized haptically with objects that underwent relative horizontal or vertical motion while maintaining a constant spatial relationship on the other axes (Fig. 5a, b). The infants produced these motions actively, by pushing and pulling on the handles. For purposes of comparison, infants in a third condition were familiarized haptically with objects that were rigidly connected and underwent no relative motion (Figure 5c), and infants in a fourth, baseline condition received no haptic familiarization. Perception of object boundaries was tested by measuring infants' looking times to visual displays of connected versus spatially separated objects (see Fig. 5), and then comparing the looking preferences obtained in each experimental condition with one another and with the preferences of the infants in the baseline condition. If the infants in two conditions with constrained relative motion perceived the handles as connected, then they were expected to look longer at the separated visual display, relative to baseline. Such a preference is predicted by the thesis that modality-specific mechanisms, optimally tuned to informative surface motions, underlie object perception in infancy. In contrast, if the infants in the two relative motion conditions perceived the handles as distinct and unconnected bodies, then they were expected to look longer at the connected visual display, both relative to baseline and relative to the infants who were habituated to the rigidly connected objects. The latter findings are predicted by the thesis that an amodal mechanism underlies object perception in infancy.

Methods

Subjects

Participants were 32 infants ranging in age from 4 months, 3 days to 5 months, 0 days ($M = 4$ months, 16 days). The 18 boys and 14 girls were born of full-term

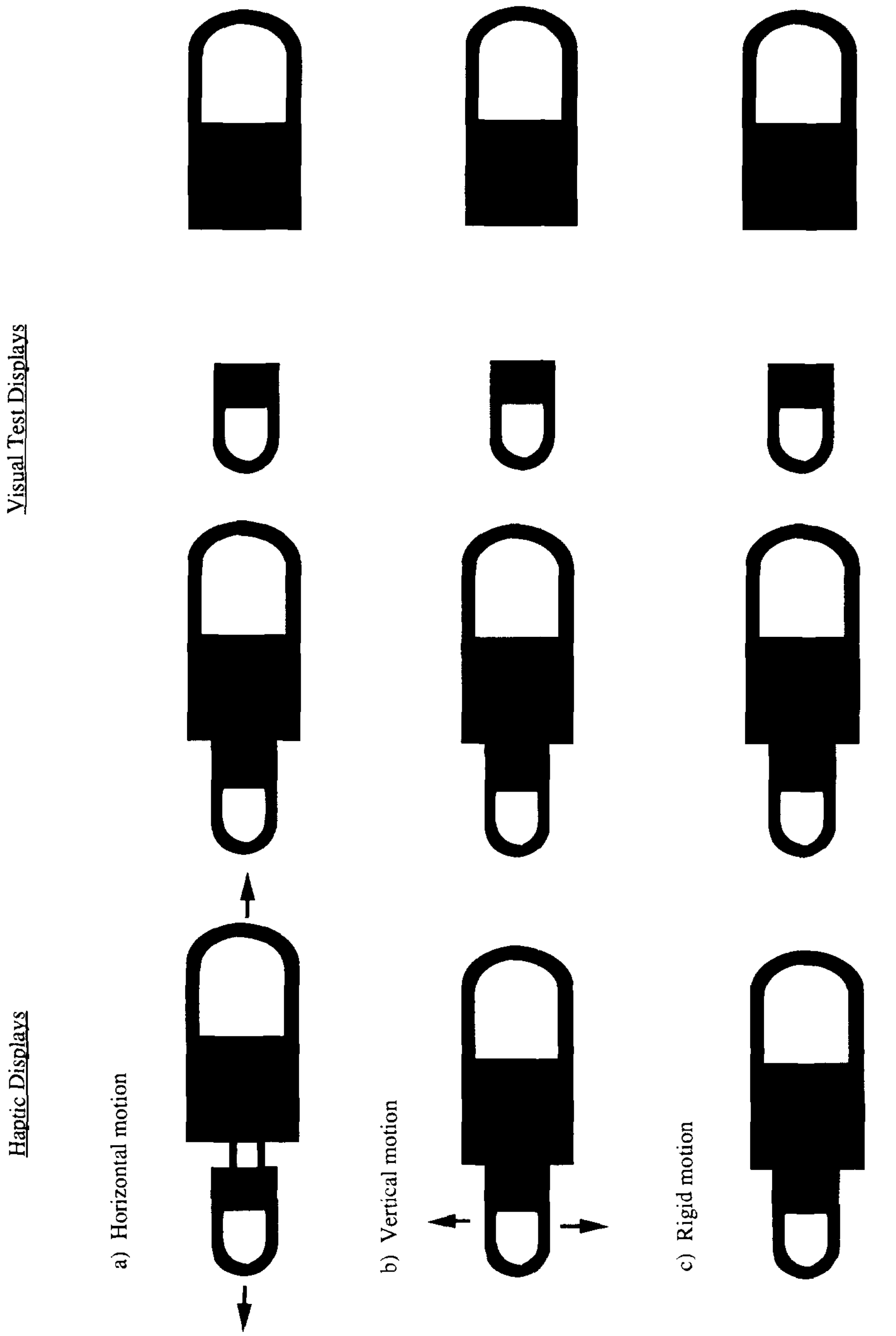

Figure 5. Schematic depiction of the displays for Experiment 2.

pregnancies, were in good health, and resided in Paris. An additional 29 subjects were eliminated because of procedural errors (7), fussiness (4), failure to meet the initial looking time criterion (3), or failure to produce the relative motion of the object (15; see below).

Displays and apparatus

Each infant sat in a semi-reclining canvas seat that permitted free movement of the hands and arms. The seat was placed within a large white experimental box facing a white curtain, with white side panels that shielded the infant from the surrounding room. During the haptic familiarization period, a white square cloth was suspended over the infant's body such that two adjacent corners were attached to the infant seat below the infant's neck and the other corners were attached to the front of the display at the infant's eye level. The cloth therefore blocked the infant's view of his or her body while leaving the arms free to move. This cloth was removed during the visual test, and the white curtain parted to reveal each test display. A video camera, positioned just under the visual displays, permitted observation of the infant's hands and body during the haptic familiarization period, and observation of the infant's head and eyes during the visual test.

Figure 5 presents the haptic object assembly and the visual displays. The haptic assemblies were the same as those presented to adults except for their size: 25% smaller. The visual displays consisted of two wooden handles of the same dimensions. In the one-object display, the two handles formed a single, connected object. In the two-object display, the two handles were separated by a gap of 14.5 cm and thus formed two distinct objects. Each visual display was mounted 10 cm in front of a white 40×20 cm panel by concealed metal rods. The panel was suspended from the front of the enclosure by strings that were hidden behind the curtain. During the visual test trials, the panel containing a visual display was agitated, such that the display underwent a rigid, jiggling motion. At its distance of 50 cm from the baby, the one-object display spanned an area of $26° \times 7°$, and the two-object display spanned $34° \times 7°$.

Design

Equal numbers of infants participated in the four conditions: relative horizontal motion, relative vertical motion, rigid motion, and baseline. Within each condition, the order of visual test trials (one-object first vs. two-object first) and the positions of the handles (smaller handle on the left vs. on the right) were orthogonally counterbalanced.

Procedure

Although Experiment 2 followed the method of Streri and Spelke (1988, 1989) as far as possible, some changes in procedure were necessary. During pilot research, it was observed that the infants in the horizontal motion condition did not spontaneously discover the relative motion: they moved the object assembly as one rigid unit. In order to facilitate the discovery of the horizontal motion, each infant in the horizontal motion condition was given a familiarization period before the main experiment. This period began as soon as the infant was seated and the cloth was positioned over his or her body. The experimenter, seated in front of and to the right of the infant, placed the assembly in the infant's hands, and then she placed her hands over the hands of the infant and produced the relative motion for 15 s. The habituation sequence began immediately after this familiarization period.

At the start of each habituation trial, the infant was given an object assembly in the position indicated in Fig. 5, and the infant was allowed to manipulate the object assembly at will. After giving the infant the assembly, the experimenter moved behind and to the right of the infant, and a second experimenter observed the infant's activity on the video monitor. In the horizontal motion condition, the infant now could produce the motion that had been demonstrated by the experimenter. In the vertical motion condition, the infant was allowed to discover the relative motion by herself, either by moving the small handle up and down actively or by allowing the small handle to fall in response to gravity. As in previous research (Hatwell, 1986; Streri & Spelke, 1988, 1989), infants tended to explore an assembly by grasping the handles and displacing them, but not by moving their fingers over the assembly so as to contact its center. When an infant released either one or both handles after holding both handles for at least 1 s, the second experimenter signaled the end of the trial to the first experimenter, who removed the other handle if necessary and then placed the handles in the infant's two hands again, beginning the second trial. A trial also was ended after 90 s of continuous holding. Trials were continued until 15 trials were presented or a criterion of habituation had been met, whichever came first. The criterion was a 50% decline in holding time on 3 successive trials, relative to holding time on the first 3 consecutive trials for which the total holding time equalled or exceeded 30 s. Every infant therefore received between 6 and 15 habituation trials.

After the last habituation trial, the white cloth was removed to reveal the entire enclosure with the curtain covering the visual display area. The second experimenter placed a visual display behind the curtain, out of the infant's view, and jiggled it. Once the display began to move, the second experimenter parted the curtain to reveal the test display, and the first test trial began. The trial continued until the infant had looked away for 1 s after looking at the display for at least 1 s. At the end of the trial, the curtain was again closed in front of the display and the displays were changed. A total of 6 test trials were given, in which the two displays appeared in alternation. The first experimenter coded looking time by observing the infant's eyes on the video monitor. He recorded looking time by pressing a key on a microprocessor, which stored all the data. The first experimenter was not able to see the test displays and did not know which display was presented on a given trial. The same test procedure was followed for the infants in the baseline condition. Testing began as soon as the infant was seated.

In order to ensure that every infant in the final sample had adequate exposure to the critical motion of the haptic assembly, infants were retained in the sample only if (a) they produced the relative motion at least once on at least half the habituation trials, and (b) they manipulated the assembly for at least 30 s during three consecutive habituation trials. Decisions to reject an infant were made by two observers who had not been present during the experiment itself, and who calculated holding times and assessed manipulation patterns from the video record of the experiment. During this coding, the observers were not aware of the infant's performance on the visual test.

Test trial looking times were coded from the video record by the same two observers. Neither the visual displays nor the curtain that covered a display between trials appeared on the video record; trial onset was indicated by the behavior of the baby, who looked at the display after the curtain was parted. The observers therefore coded an infant's looking time in ignorance of the particular display the infant viewed on any given trial and of the time when the experimenters had decided to end the trial. Inter-observer reliability was assessed by calculating the total test session looking time recorded for each baby by the video observers and by the original live observer, and by computing the correlation coefficient between these two recordings. Reliability was high, r (31) = .94.

Results

Characteristics of the haptic habituation phase are presented in Table 1(a–c) and in Fig. 6. Exploration times were similar to those obtained in past experiments

Table 1. *Characteristics of haptic habituation*

	Mean holding time first 3 trials (s)	Mean number of trials	Mean total holding time(s)
a. Active horizontal motion	58	8	117
b. Active vertical motion	77	7	116
c. Active rigid motion	91	8	130
d. Passive horizontal motion	98	7	160
e. Passive vertical motion	94	8	161

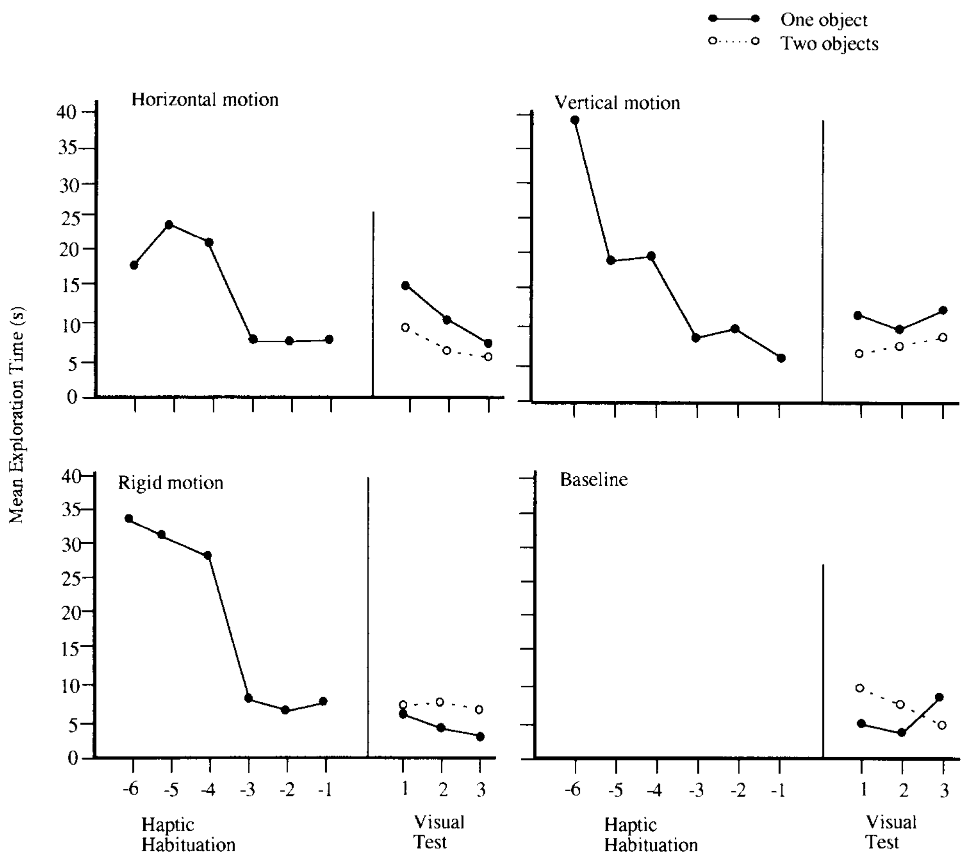

Figure 6. *Mean holding time during the last 6 habituation trials and mean looking time during the 6 test trials by the infants in Experiment 2.*

(Streri & Spelke, 1988, 1989). Analyses of variance comparing across the different conditions revealed no differences in initial holding times, total holding times, or number of habituation trials for the infants who manipulated the vertical motion, horizontal motion, or rigid motion assemblies, all $F\text{s} < 1$. Informal observations of the videotapes suggested that infants produced the common motion by displacing the handles together vertically and horizontally, and that they produced the relative motions by displacing one handle vertically or horizontally while holding the other handle at rest. Infants rarely displaced the relative motion displays far enough to arrive at the endpoints of the motion.

Figure 6 also presents the mean looking times on the 6 visual test trials. In the horizontal motion condition, all 8 infants looked longer at the connected test display ($p < .01$, sign test); in the vertical motion condition, 7 infants looked longer at the connected test display and 1 infant looked equally at the two displays ($p < .02$, sign test). In contrast, 7 infants in the rigid motion condition looked longer at the separated test display and 1 infant showed no preference ($p < .02$, sign test), and 4 infants in the baseline condition looked longer at each display. The interaction of condition (horizontal, vertical, rigid, and baseline) by test display (connected vs. separated) was the only significant effect in a 4 (condition) × 3 (test trial) × 2 (test display) analysis of variance, $F(3, 28) = 6.55$, $p < .005$.

Further 2 (condition) × 2 (test display) analyses of variance compared the looking preferences in each of the constrained relative motion conditions with the looking preferences in the rigid motion condition and in the baseline condition. The only significant effect in these analyses was the interaction of condition by test display. The infants in the horizontal motion condition showed a greater preference for the connected test display than those in the rigid motion condition, $F(1, 14) = 14.89$, $p < .002$, or the baseline condition, $F(1, 14) = 6.72$, $p < .025$. Similarly, the infants in the vertical motion condition showed a greater preference for the connected test display than those in the rigid motion condition, $F(1, 14) = 17.16$, $p < .001$, or the baseline condition, $F(1, 14) = 7.81$, $p < .02$.

Discussion

When infants are presented haptically with two objects that undergo a pattern of relative horizontal or vertical motion, they perceive the objects as distinct units. Infants perceive the distinctness of the objects, even though the objects are constrained to maintain a constant spatial relationship in all directions except one. Infants' perception of haptically presented objects thus accords with their perception of visually presented objects, consistent with the amodal mechanism hypothesis.

The comparison of the preferences in each relative motion condition with those of the preferences in the rigid motion condition confirm that perception of the separateness of the objects depended on the pattern of relative motion, and not on other properties of the displays such as the handles differing sizes and their misalignment. These findings accord with the findings of previous studies of visual perception (Hofsten & Spelke, 1985; Spelke et al., 1989) and haptic perception (Streri & Spelke, 1989) and provide further evidence for the amodal mechanism thesis.

The findings of this experiment contrast in interesting ways with those of the first experiment, in which enlarged versions of the same displays were presented to adults. Because adults perceived the relative motion assemblies as one connected object, infants' contrasting perception of these assemblies cannot plausibly be attributable to a modality-specific mechanism that is attuned, by evolution or early learning, to the most informative surface motions. Contrary to Kellman's (1988) thesis, visually and haptically presented surface motions appear to give rise to the same perceptions of object boundaries in infants, even when these motions specify different object arrangements in the visual and the haptic modes and are perceived differently by adults. In the General discussion, we consider possible reasons why perception of these objects changes after infancy.

EXPERIMENT 3

The next experiment investigated whether relative motion in a single direction specifies the separateness of two haptically presented objects when the relative motion is not produced by the infant. In the two conditions of this experiment, infants held either the horizontal motion assembly or the vertical motion assembly while the center of the assembly was also held by an experimenter. The experimenter produced the appropriate motion for the infant, without touching the infant's hands, throughout the series of haptic habituation trials. Perception of the connectedness or separateness of the objects was assessed by means of the same visual preference test as in Experiment 2. These preferences were compared with the preferences obtained in the baseline condition and in the constrained relative motion conditions of Experiment 2.

Methods

The methods were the same in Experiment 2, except as follows.

Subjects

Participants were 16 infants (8 boys, 8 girls) aged 4 months, 1 day to 5 months, 0 days ($M = 4$ months, 21 days). Six additional subjects were eliminated because of fussiness (3) or experimenter error (3).

Displays, design and procedure

Half the subjects were habituated to the horizontal motion assembly (Fig. 3a) and half to the vertical motion assembly (Fig. 3b). As soon as an assembly was placed in the baby's hands, the experimenter grasped the inside edges of the two handles, without touching the baby's hands, and produced the relative motion. Because the infants in the active motion condition did not tend to displace the objects abruptly to the endpoints of the relative motion, the experimenter stopped each motion gradually just short of those endpoints. The motion continued until the infant released one or both handles, whereupon the experimenter again placed the handles in the infant's hands and began the motion anew. Inter-observer reliability, calculated as in Experiment 2, was high, $r\ (15) = .96$.

Analyses

Holding times and looking times in the two conditions of Experiment 3 were compared with the holding times and looking times in the corresponding horizontal and vertical motion conditions of Experiment 2: this comparison tests directly for the effect of active versus passive motion on infant's exploration and perception of the objects. In addition, looking times in each condition of Experiment 3 were compared with the looking times in the baseline condition of Experiment 2. This comparison tests whether infants perceived each assembly in Experiment 3 as two separate objects.

Results

Table 1 (d, e) and Fig. 7 present the characteristics of the haptic habituation period. Haptic exploration times were somewhat longer in the passive motion conditions of Experiment 3 than in the corresponding active motion conditions of Experiment 2. A series of 2 (activity: active vs. passive) × 2 (direction: vertical vs. horizontal) analyses of variance revealed that this effect of activity was significant for the total holding time measure, $F(1, 28) = 4.23$, $p < .05$, but not for the other measures. No other effects emerged from these analyses.

Figure 7 presents the mean looking times on the visual test trials. The infants in each condition looked about equally at the one-object and the two-object test displays. In the passive horizontal motion condition, 3 infants looked longer at the connected test display, 4 infants looked longer at the separated test display, and 1 infant looked equally at the two displays. In the passive vertical condition, 4 infants looked longer at the connected test display, 2 infants looked longer at the separated test display, and 2 infants looked equally at the two test displays.

Looking times during the two conditions of Experiment 3 were compared with looking times during the corresponding relative motion conditions of Experiment 2 by a 2 (motion: active vs. passive) × 2 (test display: one-object vs. two-object) analysis of variance. This analysis revealed a significant main effect of display, $F(1, 30) = 5.67$, $p < .025$, and a motion by display interaction, $F(1, 30) = 5.42$, $p < .05$. Whereas infants tended overall to look longer at the one-object display, this tendency was reliably greater in the active motion conditions.

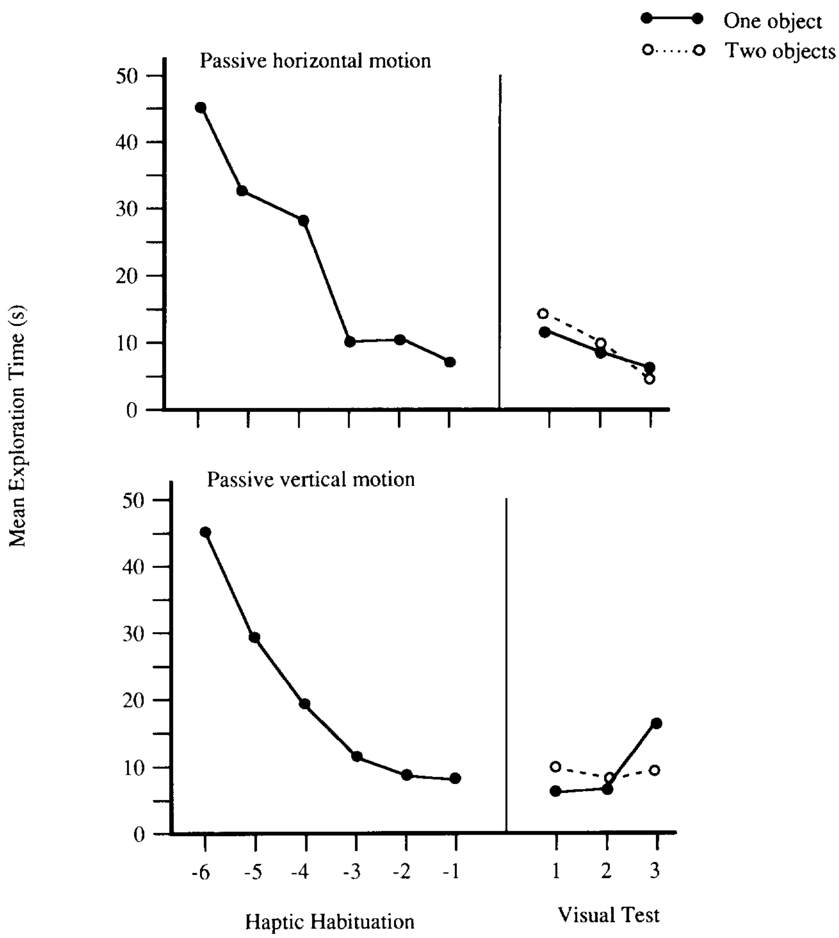

Figure 7. *Mean holding time during the last 6 habituation trials and mean looking time during the 6 test trials by the infants in Experiment 3.*

Further analyses compared the looking times in each condition of Experiment 3 with the looking times in the baseline condition of Experiment 2. These 2 (condition) × 2 (test display) analyses of variance revealed no significant effects. In particular, looking preferences did not differ from baseline in either the passive horizontal motion condition ($F < 1$) or the passive vertical motion condition ($F = 1.05$).

Discussion

When infants explored objects haptically without actively producing the objects' motions, they showed no evidence of perceiving either one connected object or two separate objects. Infants' perception differed reliably from the perception of infants who had actively produced the same motion patterns. Infants therefore appear to perceive haptically presented, moving objects more effectively when they produce the objects' motions. This finding, in turn, suggests a difference between infants' perception of seen and felt objects: when young infants view visible objects undergoing relative motion that is produced by others, they appear to perceive the objects as distinct bodies (Hofsten & Spelke, 1985; Spelke et al., 1989).

It is possible that the negative findings of Experiment 3 stem from extraneous differences between that experiment and the earlier, successful studies of visual and haptic object perception. In particular, the babies in the present experiment may have been less motivated to explore objects than those in previous studies of visual and haptic object perception, because touch is inherently an exploratory system involving active interaction with objects. In addition, the task used in the present study (haptic habituation and visual transfer) may have been more demanding than the tasks used in the previous studies of visual perception (object-directed reaching and intramodal habituation and discrimination). Infants' ability to perceive objects from motions produced by others may be revealed only in intramodal transfer tasks.

Although we cannot rule out the possibility that motivational or task factors underlie the negative findings of Experiment 3, several considerations reduce the likelihood of this possibility. First, haptic exploration times were at least as long in Experiment 3 as in Experiment 2. Infants therefore did not appear to be less interested in the present objects than in the objects in past experiments. Second, the intermodal transfer task used to assess object perception in Experiment 3 has been used successfully not only in Experiment 2 but in many previous studies (e.g., Gibson & Walker, 1984; Meltzoff & Borton, 1979; Rose, Gottfried, & Bridger, 1981; Streri, 1987; Streri & Pecheux, 1986; Streri & Spelke, 1988, 1989; see Streri, 1993, for a review). Intermodal transfer from touch to vision appears no more difficult than intramodal transfer, as long as infants are presented with displays that are discriminable within the visual and the haptic modes. For these reasons, we suggest that the negative findings of Experiment 3 reflect infants' greater difficulty perceiving haptically presented objects under conditions of passive motion. Like adults, infants appear to perceive the boundaries of haptically presented objects more clearly from patterns of relative motion that the infants produce themselves than from patterns of relative motion produced by others.

GENERAL DISCUSSION

The present experiments shed light on certain modality-specific and amodal aspects of object perception in infancy, and they support several suggestions about object perception in adults. We consider each of these suggestions in turn.

Amodal processes of object perception in infancy

In every situation yet tested, infants have been found to perceive objects under the same stimulus conditions through vision and through *active* touch. In the visual mode, infants perceive a unitary object when the visible surfaces of the object undergo a common rigid motion (Hofsten & Spelke, 1985; Kellman & Spelke, 1983; Kellman et al., 1986, 1987). Infants also perceive a unitary object in the haptic mode when the tangible surfaces of the object can only be displaced rigidly (Streri & Spelke, 1988, 1989). Visual perception of the unity and boundaries of objects is not affected by static configurational properties of the objects, such as their homogeneity in substance and the simplicity of their overall form (Hofsten & Spelke, 1985; Kellman & Spelke, 1983; Kestenbaum et al., 1987). These properties similarly fail to influence haptic perception of objects (Streri & Spelke, 1989). Finally, infants perceive two objects as distinct units if the objects undergo relative motion in one direction, even if the objects maintain constant spatial relationships in all other directions (Hofsten & Spelke, 1985; Spelke et al., 1989). Experiment 2 of the present series provides evidence that the same is true in the haptic mode: relative motion in one direction specifies, for infants, that two haptically presented objects are distinct.

The present findings are difficult to reconcile with the thesis that object perception depends on modality-specific mechanisms that respond to the same, maximally useful information (Kellman, 1988). The information provided by a pattern of relative horizontal motion appears to be different, depending on whether the motion is seen or felt. When two objects are seen to undergo relative motion in only one direction (e.g., when a box slides on a table or an animal walks on a platform), it is very likely that the objects are not connected, and that the objects' lack of relative motion in other directions stems from the action of forces such as gravity and friction. In contrast, when two objects are actively manipulated and undergo relative motion in only one direction, the objects almost certainly *are* connected in some way, because unconnected objects would move independently in all directions. Adults appear to be sensitive to this difference between seen and felt displays: they perceive the unity and connectedness of felt objects with separately movable parts, both when they are presented with objects of familiar kinds (Lederman & Klatzky, 1990) and when they are presented with unfamiliar object assemblies (Experiment 1). If object perception depended on separate visual and haptic mechanisms, each appropriately attuned to maximally informative stimulus relationships, then reactions to this relative motion should have differed in the two modes for infants as well as adults. The findings of the active motion experiments therefore provide evidence that a single, amodal mechanism serves to organize the perceived layout into objects, at least in infancy.

Modality-specific processes of object perception in infancy

Although the same motion patterns specify object unity in the visual and the haptic modes, infants must explore surfaces differently in the two modes in order to perceive objects. In the visual mode, infants and adults perceive object boundaries when viewing surfaces from a distance without influencing their motions. In the haptic mode, in contrast, infants evidently must produce surface motions actively in order to perceive object boundaries. This difference between visual and haptic object perception, which is found also in adults (Gibson, 1962; Lederman & Klatzky, 1987; Experiment 1), suggests that object perception is influenced by modality-specific as well as amodal processes.

One could explain all the effects reported here by proposing that object perception results from a two-stage process (see also Spelke, 1990). In the first stage, modality-specific perceptual mechanisms may construct a representation of the continuous, three-dimensional surface layout. Surface properties such as orientation, distance, and motion would be recovered during this stage (e.g., by processes that compute depth from binocular disparity, from optic flow, and from efferent commands to the muscles during active manipulation) and would be incorporated into a single representation. The effects of active versus passive motion on haptic perception would occur at this stage of analysis and would influence infants' perception of the arrangements and motions of the surfaces they feel. In the second stage, amodal processes may operate on the representation of the surface layout, grouping surfaces onto objects by analyzing their perceived arrangements and motions. The effects of common versus relative motion observed in Experiment 2 would occur at the second stage of analysis and would influence infants' perception of the connections among, and boundaries between, the surfaces they feel. Parallel findings therefore would be obtained in studies of infants' perception of visually and haptically presented objects, provided that infants are able to manipulate tangible objects actively and therefore perceive the objects' motions.

This view leads to predictions concerning infants' perception of surface motion in the visual and haptic modes. Infants who explore actively the objects in Fig. 3a, b should perceive the objects' relative motions. If they are subsequently presented with visible objects undergoing the same versus a different motion from that which they had felt, they should look longer at the novel motion. In contrast, infants who feel the same object motions passively should fail to perceive their motions. In a subsequent visual test, they should show no preference for a novel motion over the motion that they had felt. This failure of motion perception would locate the effect of active motion at the first stage of object perception, when modality-specific mechanisms construct a representation of surface motions. Ongoing experiments are testing these predictions.

Developmental changes in object perception

In the present experiments, infants perceived objects undergoing limited relative motion differently from adults. Whereas adults reported that such objects were connected, infants appeared to perceive them as separate bodies. This finding suggests that object perception undergoes qualitative changes over the course of development.

Unfortunately, these experiments shed little light on the nature of developmental changes in object perception. It is possible that adults and infants perceive objects undergoing constrained relative motion differently because adults perceive objects in accord with general principles that emerge after the fifth month of life. As a second possibility, adults and infants may perceive objects in accord with the same general principles, but adults' perception may be influenced, as well, by specific knowledge about objects of particular kinds, with movable parts. As a third possibility, developmental changes in object perception may stem from developmental changes in patterns of haptic exploration, and therefore changes in the nature of the information about objects that is available to perceivers. Further research, including assessments of developing object categories and detailed observations of adults' and children's exploratory activities, is needed to evaluate these possibilities.

A developmental approach to object perception

Existing research does not settle the fundamental questions about object perception with which we began. We believe, nevertheless, that the developmental approach taken here already has yielded findings that will contribute to the resolution of these questions, and that it has yielded methods that can be used to probe the mechanisms of object perception further.

The present studies of object perception resemble developmental studies of language processing. A central question in the psychology of language concerns the modality-specific or amodal character of the processes by which humans speak and understand: to what extent does language processing depend on properties of the human auditory system, on one hand, and on properties of more central systems, on the other? Experiments have addressed this question by investigating the emergence of language in a modality other than audition: the visual–gestural language of the deaf. To the extent that language depends on purely auditory processes, one would not expect parallels between the development of auditory and of visual–gestural languages; to the extent that language depends on amodal processes, then the same abilities should emerge, at the same developmental time, in the two modes.

Because the amodal mechanism thesis predicts no differences between functioning that is based on different input systems, tests of this thesis are in the awkward position of proving the null hypothesis. Given the detailed structure of language and object perception, however, a pattern of parallel findings concerning performance from the two modalities of input, both at a single age and over the course of development, gives considerable support to that thesis. Evidence for common structures, principles, and developmental timetables now abounds in the case of language development (Klima & Bellugi, 1979; Newport, 1981; Petitto & Marentette, 1991). Because less is known about the development of object perception, the case for amodal mechanisms of object perception is currently weaker. We believe, nevertheless, that developmental studies have comparable potential in these two domains.

Two recent developmental studies suggest a further direction in which to investigate modality-specific and amodal processes in object perception. First, research by Slater et al. (1990) provides evidence that the capacity to perceive object unity by analyzing the common rigid motions of visible surfaces develops between birth and 4 months. Whereas 4-month-old infants perceive a center-occluded, rigidly moving object as a single connected body, newborn infants perceive such an object as two distinct bodies separated by a gap. To date, research does not reveal when this developmental change occurs, or whether the developing processes that underlie this change occur at the first stage of perceptual analysis, when representations of the surface layout are constructed, or at the second stage, when surfaces are organized into objects. Second, research by Streri (1993) provides evidence for a developmental change in haptic perception of objects over the first $4\frac{1}{2}$ months. Again, her research does not reveal exactly when the change occurs or whether the change concerns processes of object perception or prior processes of surface and motion perception.

Given the findings of Slater et al. (1990) and of Streri (1993), the present view leads to the following predictions. Insofar as changes in surface perception occur in the first 4 months, the changes will not occur synchronously in the visual and haptic modes. Perfectly synchronous changes would occur only by an unlikely coincidence, if distinct mechanisms construct representations of surfaces from visual and haptic information. In contrast, insofar as changes in object perception occur in the first 4 months, the same changes should occur at the same time in development in both the visual and the haptic modes. Through longitudinal research, we hope to test these predictions.

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