Effects of Motion and Figural Goodness on Haptic Object Perception in Infancy

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STRERI, ARLETTE, and SPELKE, ELIZABETH, S. *Effects of Motion and Figural Goodness on Haptic Object Perception in Infancy.* CHILD DEVELOPMENT, 1989, **60**, 1111–1125. 4-month-old infants held 2 rings, 1 in each hand, out of view. The rings moved rigidly together and were either the same (Experiment 1) or different (Experiment 2) in substance, weight, texture, and shape. After haptic habituation to a ring display, patterns of preferential looking to visibly connected vs. separated rings provided evidence that the infants perceived the rings in both experiments as parts of one connected object. This perception was no weaker when the rings differed in shape and substance, even though infants were shown (Experiment 3) to detect that difference. In the haptic mode, as in the visual mode, infants appear to perceive object unity by analyzing motion but not by analyzing figural goodness. The findings suggest that an amodal mechanism underlies object perception.

Human adults perceive the surrounding environment as a layout of unitary, bounded objects. This ability is remarkable because the stimulus information for object boundaries is highly incomplete. In the visual mode, every opaque object is partly hidden: Its back is occluded by its front, and its front is usually partly occluded by other objects. Most objects, nevertheless, are perceived as complete units rather than as collections of visible fragments (Michotte, Thinès, & Crabbé, 1964). In the haptic mode,[1] only small regions of the surface layout are encountered at any given time as a perceiver explores by touching. Objects are again perceived as continuous wholes, however, not as the patches of surfaces in contact with the fingers (Gibson, 1962).

Some recent attempts to understand these abilities have focused on their early development (see Spelke, 1988, for a review). Studies of object perception in the visual mode provide evidence that 3–5-month-old infants perceive object boundaries and object unity by detecting patterns of surface motion. When a moving object is presented in front of a larger object that moves in a different direction, for example, infants perceive the objects as distinct units, even if their images overlap in the visual field (Hofsten & Spelke, 1985; see also Spelke, Hofsten, & Kestenbaum, 1989). When a moving object is presented behind a central occluder such that its two visible ends are displaced together, infants perceive the object as a complete unit that continues behind the occluder (Kellman, Gleitman, & Spelke, 1987; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986).

In contrast, young infants do not appear to perceive object unity and boundaries in accord with a general tendency to maximize "figural goodness." Experiments provide evidence that infants perceive two stationary objects of different colors, patterns, and shapes as a single unit if the objects stand adjacent to each other in any dimension, including adjacency in depth (Kestenbaum, Termine, & Spelke, 1987; see also Hofsten & Spelke, 1985; Prather & Spelke, 1982; Spelke et al., 1989). Furthermore, infants do not appear to perceive the unity of a stationary, center-occluded object of a uniform color and pat-

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[1] Following Gibson (1962), the present paper will use "haptic" to refer to all perception that is derived from active touch, regardless of the sensory pathways through which the perception arises.

[*Child Development*, 1989, **60**, 1111–1125. © 1989 by the Society for Research in Child Development, Inc.

terning and a simple and regular form (Kellman & Spelke, 1983; Schmidt & Spelke, 1988; Schmidt, Spelke, & LaMorte, 1986; Schwartz, 1982; Termine, Hrynick, Kestenbaum, Gleitman, & Spelke, 1987). Infants evidently perceive objects by analyzing the motions of surfaces so as to form units that move as wholes, but not by analyzing the colors, textures, and shapes of surfaces so as to form units of maximal simplicity and regularity.

To our knowledge, only one series of studies has focused on infants' haptic perception of object unity (Streri & Spelke, 1988). Since it provides the basis for the present experiments, it will be described in some detail. Streri and Spelke (1988) presented 4-month-old infants with two rings, one in each hand, under a cover that blocked the infants' view of the rings and of their own bodies. In one condition, the rings could only be moved together rigidly. In the other condition, the rings could be pushed together, pulled apart, and displaced independently.

A series of experiments, using a haptic habituation and visual transfer method (Streri, 1987; Streri & Pêcheux, 1986a, 1986b), investigated infants' exploration and perception of the ring displays. Infants were found to explore the rings actively by displacing them. Whereas the rigidly connected rings could only be moved together, the infants tended to move the independently movable rings in opposite directions. Infants also were found to discriminate these motion patterns and to transfer the motion discrimination from touch to vision. After habituating to the rigidly movable rings, infants looked longer at a visual display of the same rings moving independently than at a visual display of the rings moving rigidly; after habituating to the independently movable rings, infants showed the reverse looking preference. Habituation generalized, to some extent, from the haptic mode to the visual mode.

Most important, these experiments provided evidence that the felt motion patterns of the rings influenced infants' perception of object unity and boundaries. After habituating to the rigidly movable rings, infants looked longer at a visual display in which the two rings appeared as distinct objects separated by a gap than at a visual display in which the two rings constituted the ends of a single, connected object. Infants evidently perceived the rigidly movable rings as a connected body that extended between their hands. After habituating to the independently movable rings, infants showed the reverse looking preference. Infants evidently perceived the independently movable rings as two separate bodies, one in each hand.

Infants thus appear to perceive object unity and boundaries under the same conditions in the visual and the haptic modes. They perceive a unitary, partially seen or felt object by detecting the common motions of surfaces, and they perceive two distinct, partially seen or felt objects by detecting the relative motions of surfaces. This convergence of findings is striking, because the visual and haptic experiments provided different kinds of kinetic information for object boundaries. In the studies of visual perception, infants watched objects that moved independently of themselves. In the studies of haptic perception, infants manipulated objects, producing the very motions and pressure patterns that provided information about object boundaries.

The above findings raise the possibility that object perception depends on a single, relatively central mechanism that accepts input from either the visual or the haptic system. This possibility has not often been considered in theoretical accounts of object perception. Theorists as diverse as Hebb (1949) and Koffka (1935) have proposed that visual perception of object boundaries depends on innate, automatic processes operating on proximal visual arrays to segregate "figure" from "ground." Even theorists such as Brunswik (1956) and Helmholtz (1924), who believed that object perception depends on learned, inference-like processes, proposed that those processes operate on features of the proximal visual array such as interruptedness of edges (Helmholtz, 1924) or proximity of retinal elements (Brunswik & Kamiya, 1953). According to all these views, the organization of sensory arrays into objects occurs early in perceptual analysis, by virtue of modality-specific mechanisms.

Nevertheless, the possibility that objects are perceived by a relatively central mechanism is consistent with recent studies of visual perception of objects in infancy and with some computational analyses of vision. Studies of infant perception provide evidence that the mechanisms of object perception take as input a representation of the three-dimensional surface layout; they do not operate on lower-level representations of retinal elements and relations (Kellman et al., 1986, 1987). Research in computational vision suggests why this might be the case. Although surface arrangements and motions can be computed by mechanisms that operate on relatively low-level visual representations (see Marr, 1982; Yuille & Ullman, in press), no computational procedure has yet been devised that can segment low-level representations into objects in any general way (Huttenlocher, 1988; Marr, 1982; but see Lowe, 1985). The problem of perceiving objects may be more tractable if the input to the object segmentation process is a representation of three-dimensional surface arrangements and motions (Marr, 1982). There would seem to be no reason why such a process should be specific to vision.

The present experiments were undertaken for two reasons. First, they attempt to replicate and extend one of the principal findings of Streri and Spelke (1988) by investigating infants' haptic perception of rigidly movable objects of new shapes, substances, and textures. Second, they attempt to test a further prediction that follows from the hypothesis that a single, amodal mechanism underlies infants' perception of objects. According to that hypothesis, object perception should succeed *and fail* under the same conditions in the visual and haptic modes. Since young infants evidently do not perceive the boundaries of the objects they see by analyzing static configurational properties of surface arrays so as to maximize figural goodness, infants also should not perceive objects they feel through such an analysis. The present experiments therefore investigated whether figural goodness affects perception of object unity when young infants explore by touching.

How might this test be conducted? In the visual mode, sensitivity to static, configurational information for object unity has been tested in two ways. First, subjects have been presented with stationary, partly occluded surfaces. In different conditions, the colors, textures, and shapes of the surfaces specified either that they formed a single, connected object with an occluded center or that they formed two distinct objects separated by a gap behind the occluder. These configurational properties were found to influence object perception for adults (Kellman & Spelke, 1983; Schmidt, 1985; Termine et al., 1987) and for 2–3-year-old children (Schmidt, 1985) but not for young infants (Kellman & Spelke, 1983; Schmidt & Spelke, 1988; Schmidt et al., 1986). Infants appeared to have no definite perception of object unity or object boundaries in stationary occlusion displays.

Although the above studies suggested that young infants fail to perceive visible objects by maximizing figural goodness, that suggestion could be questioned on two grounds. First, infants may fail to organize stationary displays into units of maximal goodness because stationary displays are not sufficiently interesting to them: Infants may fail to attend to the configurational properties of motionless displays.[2] Second, infants may be "conservative" in their perception of partly hidden objects: They may perceive a center-occluded object as a connected unit only if its visible surfaces are united both by common motion and by figural goodness. Stationary displays may contain information for object unity, but this information may not be sufficient, by itself, for young infants.

The second method addressed these problems. Subjects were shown two partly occluded surfaces that underwent a common motion. In different conditions, the static configurational properties of the surfaces either united them further or served to separate them. For adults, perception of object unity was stronger when figural goodness reinforced that perception than when it worked against it (Kellman & Spelke, 1983). For infants, in contrast, perception of object unity was strong for all the displays and was unaffected by figural goodness (Kellman & Spelke, 1983). These studies provide evidence that common motion is both necessary and sufficient for infants' perception of object unity in the visual mode. Static configural relations do not influence that perception, even when infants view moving displays that command considerable attention.

The first two experiments to be reported followed the logic of the second method. Infants were presented with an assembly of two rings, one ring in each hand, that moved as one rigid unit. In Experiment 1, the rings were of the same substance, weight, texture, and shape. In Experiment 2, the rings differed in substance, weight, texture, and shape. Perception of the unity of the rings was tested by habituating the infants to the haptically presented ring assembly and then presenting visual displays in which the same rings were either visibly connected or visibly separated by a gap. Infants in separate baseline conditions viewed the visual test displays with no prior habituation sequence. Following Streri and Spelke (1988), the infants in Experiment 1 were expected to look longer at the separated ring display than at

[2] Experiments by Kellman and Spelke (1983, Experiment 3) and by Schmidt and Spelke (1988, Experiment 4) provide evidence that infants do detect and attend to stationary occlusion displays, contrary to this suggestion.

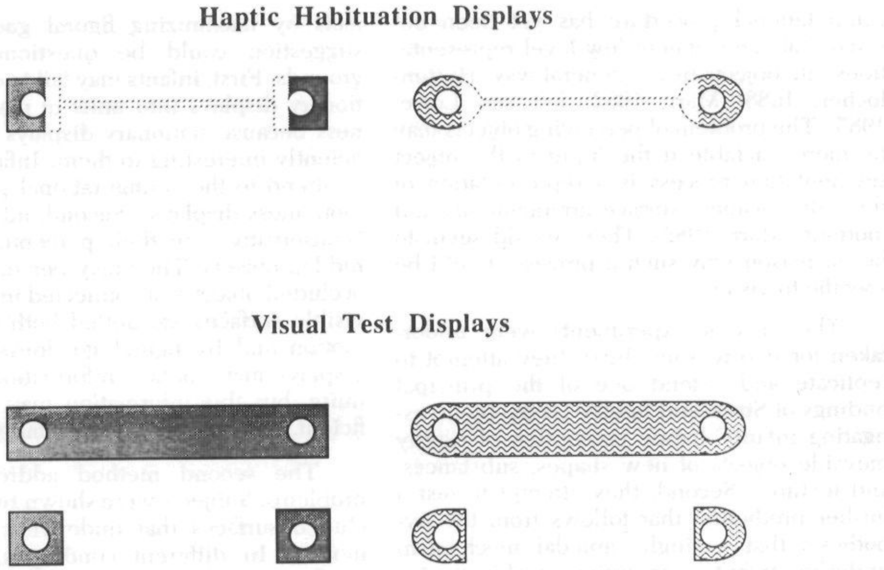

FIG. 1.—Haptic habituation displays and visual test displays for Experiment 1. Dotted lines indicate the portions of the habituation display not felt by the infant.

the connected ring display, relative to baseline. If figural goodness affects haptic object perception, this looking preference should have been weaker in Experiment 2. If figural goodness does not influence haptic object perception, this preference should have been observed with equal strength in the two experiments.

Experiment 1

Method

The method of this experiment was the same as that of Streri and Spelke (1988, Experiment 4), except for the stimulus displays. Infants were presented with two rings that could be united to form one object of a uniform substance and a simple shape. For some subjects, the rings were rigid, heavy, smooth, and rectangular; for the other subjects, the rings were flexible, light, rough, and rounded.

Subjects.—Participants were 24 infants, 14 boys and 10 girls, residing in Paris. The infants ranged in age from 3 months, 19 days to 4 months, 27 days (mean age, 4 months, 13 days).

Displays and apparatus.—Each infant sat in a semireclining canvas seat that permitted free movement of the hands and arms. The infant faced a three-sided white enclosure whose side panels shielded him or her from the surrounding room and whose front panel (80 cm high × 80 cm wide × 50 cm distant) served as the background for the visual displays. During the haptic familiarization period, a white cloth was tied at one end to the infant seat and at the other end to the front panel in order to block the infant's view of his or her body while leaving the arms free to move. This cloth was removed during the visual test. A video camera was positioned behind a hole in the center of the front panel, just under the visual displays (see below). This camera permitted observation of the infant's hands and body during the haptic familiarization period, as well as the infant's head and eyes during the visual test.

The haptically presented objects were two ring assemblies (Fig. 1, top). In one assembly, the rings were square in shape (4.5 cm on a side) and were made of painted wood that was rigid in substance, smooth in texture, and rather heavy (7 grams per ring). In the other assembly, the rings were rounded in shape (4.5 cm in height and 5.5 cm in width) and were made of unpainted foam rubber that was flexible in substance, rough in texture, and rather light (4 grams per ring). The rings in each assembly were mounted on a .5-cm thick, metal connecting bar (not felt by the subjects) so that their edges were aligned and their centers were 19 cm apart. Infants held the rings with their thumbs through the central holes and their fingers around the outer edges. From this position, the square rings could appear to form a single, connected object of a rectangular shape, and the round rings could appear to form a single, connected object of an ovoid shape. The rings in both assemblies moved rigidly together when the infant displaced them.

The visually presented displays were the same size, texture, and apparently the same substance as the haptically presented displays (actually, styrofoam was substituted for foam rubber in the rounded display). Two visual displays were created for each haptic display: a *connected display,* in which two rings were joined to form a single object of a maximally simple shape, and a *separated display,* in which two rings were separated by a 15-cm visible gap (Fig. 1, bottom). Both the connected and the separated visual displays were identical in shape to the corresponding haptic ring assembly at the places where the infant had been able to feel the ring assembly. Both visual displays differed from the corresponding haptic display, however, at places the infant could not feel. Whereas the haptic ring assembly consisted of two square or rounded rings connected by a bar, the visual displays consisted either of a long, rectangular or rounded object of an uniform shape and homogeneous material (connected display) or of the two ends of such an object, separated by a rectangular gap (separated display).

Each visual display was painted red and was mounted on a 40 × 25-cm white board by 10-cm metal rods. The rods, which stood behind the rings, were not visible to the infant. The board containing a ring display was suspended from the front panel of the white enclosure by 9-cm white strings attached to the top of that panel. The board was agitated before each test, causing the rings to undergo a rigid, jiggling motion. At its distance of 35 cm from the baby, each ring display subtended 40° × 6°. A white 35 × 50-cm screen held in front of the display board blocked the infant's view of the rings between trials.

Design.—Twelve infants were assigned to each condition, experimental and baseline. Six subjects in each condition were presented with the rigid rings and six subjects were presented with the flexible rings. The infants in the experimental condition received a haptic habituation sequence followed by a visual test in which connected and separated displays corresponding to the rings they had felt were presented on six alternating trials. The infants in the baseline condition received the same visual test with no prior habituation sequence. The latter infants also participated in the baseline condition of Experiment 2 (see below); half participated in the Experiment 2 baseline condition first. The order of test trials (connected display first vs. separated display first) was counterbalanced across the infants in each condition.

Procedure.—For the infants in the experimental condition, the experiment began as soon as an infant was seated and the cloth was positioned over his or her body. An experimenter, seated behind and to the right of the infant, placed the rings in the infant's two hands, and then a second experimenter observed the infant's activity on the video monitor. The infant was allowed to manipulate the ring assembly at will. As in previous research (Hatwell, 1986; Streri & Spelke, 1988), infants tended to explore the assembly by grasping the rings and displacing them. Infants rarely moved their fingers over the assembly, however, so as to contact parts of the assembly that they did not hold initially.[3] When an infant released either one or both rings after holding both rings for at least 1 sec, the second experimenter signaled the end of the trial to the first experimenter, who removed the other ring if necessary and then presented both rings again, beginning the second trial. A trial was also ended after 90 sec of continuous holding. Trials were continued until 15 trials had been presented or until a criterion of habituation had been met, whichever came first. The criterion was a 50% decline in holding time on three successive trials, relative to holding time on the first three consecutive trials for which the total holding time equaled or exceeded 30 sec (for all but six of the 40 infants in the present habituation experiments, these were the first three trials). Every infant therefore received between six and 15 habituation trials.

After the last habituation trial, the white cloth was removed to reveal the entire enclosure with the screen covering the visual display area. The second experimenter placed a ring display behind the screen, out of the infant's view, and jiggled it.[4] Once the display began to move, the first experimenter lifted

[3] To ensure that infants' test trial performance was not affected by direct tactile exposure to the bar that connected the rings in the haptic assembly, infants' exploratory activity was monitored throughout the habituation sequence, and all occasions on which an infant touched the central connector between the rings were recorded. Touching the connector was rare: It occurred on only 4% of the habituation trials, in a total of four subjects across Experiments 1 and 2. The findings reported here are unchanged if these subjects are eliminated from the analyses.

[4] The experimenter was aware of the display presented on each trial but was uninformed about the purposes and hypotheses of the study. She was trained to set the display in motion with a single gesture.

TABLE 1

CHARACTERISTICS OF HAPTIC HABITUATION

	Holding Time, First 3 Trials (sec)	Number of Trials	Total Holding Time (sec)
a. Experiment 1:			
Rigid rings	69.0 (46.2)	7.5 (2.0)	114.8 (36.3)
Flexible rings	72.5 (44.0)	8.1 (3.4)	127.7 (49.9)
Total	70.8 (43.0)	7.8 (2.7)	121.2 (42.1)
b. Experiment 2:			
Rigid right	58.0 (37.2)	7.2 (1.8)	79.2 (30.6)
Rigid left	80.0 (44.2)	8.0 (2.8)	181.0 (93.8)
Total	69.0 (40.6)	7.6 (2.3)	130.1 (85.1)
c. Experiment 3:			
Identical rings	50.2 (36.2)	8.2 (2.2)	85.6 (36.0)
Different rings	76.2 (39.6)	8.0 (3.3)	139.5 (86.1)
Total	63.4 (39.1)	8.1 (2.7)	112.6 (69.5)

NOTE.—The table gives the means (and standard deviations) for each display condition of each experiment and for each experiment as a whole.

the screen and the first test trial began. The trial continued until the infant had looked away for 2 sec, after looking at the display for at least 1 sec. At the end of the trial, the screen was again placed in front of the display and the displays were changed. The first and second experimenter jointly decided when to end each trial by observing the infant's eyes through the video camera and on the video monitor, respectively. The same test procedure was followed for the infants in the baseline condition. Testing began either as soon as the infant was seated or as soon as he or she completed the baseline test for Experiment 2.

Holding times during the habituation period were later recalculated from the video record by the first experimenter. Her calculations revealed that all the subjects had met the criterion of habituation as it had been determined during the experiment. Test trial looking times were coded from the video record by both experimenters working together. Neither the visual displays nor the screen that covered a display between trials appeared on the video record; trial onset was indicated by a faint voice. 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. The observers were also ignorant of each subject's condition (experimental vs. baseline). A separate pair of observers coded the looking times of 12 randomly chosen subjects, six in each condition. Reliability between the two pairs of observers was high, $r = .95$.

Results

Habituation period.—Characteristics of the habituation phase are presented in Table 1*a* and Figure 2. Infants explored the rigid rings and the flexible rings about equally, all

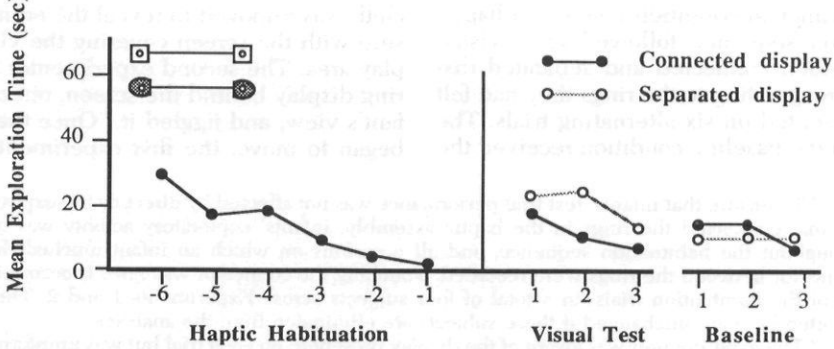

FIG. 2.—Looking times to connected and separated ring displays after haptic habituation to rings united both by common motion and by figural goodness, or after no habituation.

t's $(10) < 1$. All the infants met the criterion of habituation within the allotted 15 trials.

Test period.—Figure 2 presents the looking times during the visual test. The infants in the experimental condition looked longer at the separated ring display, whereas the infants in the baseline condition showed no consistent preference between the displays. Ten subjects in the experimental condition looked longer at the separated ring display, one subject looked longer at the connected display, and one subject looked equally at the two displays ($p < .01$, sign test). In the baseline condition, five subjects looked longer at the connected display, five subjects looked longer at the separated display, and two subjects looked equally at the two displays ($p > .20$).

In order to assess whether looking patterns in the baseline condition were affected by the order of the baseline tests for the displays of Experiments 1 and 2, a 2 (baseline test order) × 3 (trial pair) × 2 (test display: connected rings vs. separated rings) mixed-factor ANOVA was performed on the test trial looking times in the baseline condition of Experiment 1. This analysis revealed no differences in looking times or looking preferences between the infants who viewed the test displays first and those who viewed the test displays after the baseline test for Experiment 2, all F's < 2.9, $p > .10$. Accordingly, the infants in the baseline condition were considered as a single group.

The principal analysis was a 2 (condition: experimental vs. baseline) × 2 (ring assembly: rigid vs. flexible), × 3 (trial pair) × 2 (test display: connected rings vs. separated rings) ANOVA with the last two factors within subjects. This analysis revealed a significant interaction of condition × test display, $F(1,20) = 7.55$, $p < .02$: The infants in the experimental condition showed a larger looking preference for the separated test display than did the infants in the baseline condition. The only other significant factors were a main effect of condition, $F(1,20) = 5.10$, $p < .05$, and a main effect of trial pair, $F(2,40) = 5.24$, $p < .01$: Looking times were higher, on average, in the experimental condition, and they were higher on the earlier test trials.

Discussion

Experiment 1 replicates and extends the findings of Streri and Spelke (1988). Infants who were habituated to rigidly movable rings of a common substance and a simple shape subsequently looked longer at a visual display in which those rings appeared as two separate objects than at a visual display in which those rings formed the ends of one connected object. This looking preference cannot be attributed to baseline differences in the attractiveness of the two displays. It provides evidence that the infants perceived the rigidly movable rings as one connected body. A common, manually produced motion has now been found to evoke perception of object unity in two separate investigations involving three different displays.

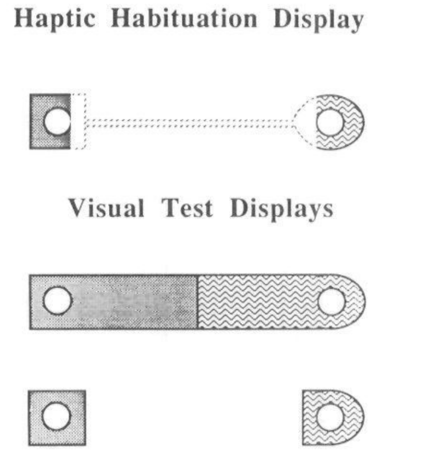

FIG. 3.—Haptic habituation display and visual test displays for Experiment 2. For half the infants, the left-right positions of the two rings were reversed.

Experiment 2

Experiment 2 investigated whether haptic perception of object unity is affected by figural goodness. Infants were presented with two rigidly movable rings that differed in substance and shape: One ring was hard, heavy, smooth, and square, and the other ring was soft, light, rough, and round. Perception of the connectiveness of the rings was tested as in Experiment 1.

Method

Subjects.—Participants were 24 infants, 12 boys and 12 girls, residing in Paris. The infants' ages ranged from 3 months, 19 days to 5 months, 5 days (mean age, 4 months, 17 days). One additional subject was eliminated from the study because of fussiness.

Displays and apparatus.—These were the same as in Experiment 1, except for the ring displays. For the haptic habituation sequence, the ring assemblies consisted of one ring from each of the two assemblies of Experiment 1, joined by the metal bar. Thus, the rings moved together but differed in substance, weight, texture, and shape (Fig. 3,

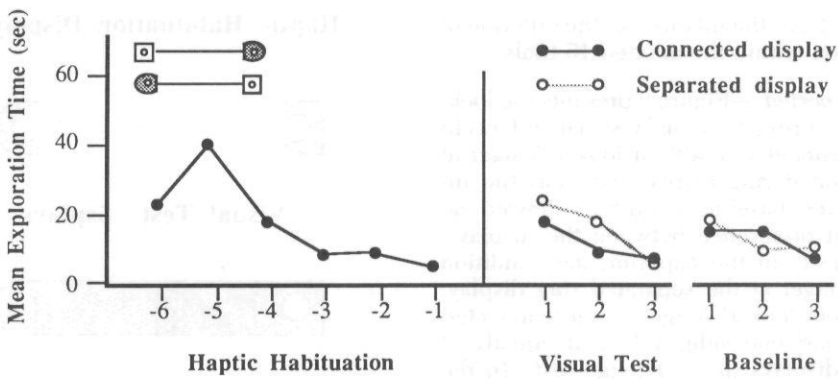

FIG. 4.—Looking times to connected and separated ring displays after haptic habituation to rings united by common motion but not by figural goodness, or after no habituation.

top). For the visual test, the connected display consisted of half of each connected display from Experiment 1, and the separated display consisted of one ring from each separated display of Experiment 1 with a 15-cm gap between them (Fig. 3, bottom).

Design and procedure.—These were the same as in Experiment 1, except as follows. Half the infants in the experimental and baseline conditions were presented with the rigid ring on the right and half were presented with the rigid ring on the left. The infants in the experimental condition were presented with the rigid ring on the same side during habituation and test. Subsequent blind coding from the video record revealed that the habituation criterion had been determined correctly for all the subjects. Interobserver reliability averaged .94 during the visual test.

Results

Habituation period.—Characteristics of the habituation phase appear in Table 1*b* and Figure 4. The infants who were presented with the rigid ring in the left hand tended to hold the rings longer than those who were presented with the rigid ring in the right hand. This difference was significant for the total holding time measure, $t(10) = 2.45$, $p < .05$, although not for the other measures, both t's < 1. All the infants met the criterion of habituation within the allotted 15 trials.

Test period.—Looking times during the visual test appear in Figure 4. The infants in the experimental condition looked longer at the separated ring display, whereas the infants in the baseline condition showed no consistent preference between the displays. In the experimental condition, 10 subjects looked longer at the separated display and two subjects looked longer at the connected display ($p < .02$, sign test). In the baseline condition, six subjects looked longer at the separated display and six subjects looked longer at the connected display ($p > .20$).

A 2 (baseline test order) × 3 (trial pair) × 2 (test display) mixed-factor ANOVA on the test trial looking times in the baseline condition of Experiment 2 revealed a significant effect of the order of the baseline tests for Experiment 1 and Experiment 2, $F(1,10) = 10.08$, $p < .025$. The infants who were given the present baseline test first showed a longer mean total looking time at the test displays (93.0 sec) than did the infants who were given the present baseline test after the test from Experiment 1 (42.8 sec). The mean total looking time during the test for the experimental condition (87.6 sec) was similar to that of the baseline infants who received the present test first. Accordingly, the test trial looking times in the experimental and the baseline conditions were analyzed in two ways: by an analysis that considered all the infants in the baseline condition as a single group, and by an analysis that considered just the six infants in the baseline condition who received the present test trials before those of Experiment 1.

The first of these analyses was comparable to that of Experiment 1: a 2 (condition) × 2 (ring display: rigid left vs. rigid right) × 3 (trial pair) × 2 (test display) ANOVA. This analysis revealed a significant interaction of condition × test display, $F(1,20) = 7.19$, $p < .02$, and a significant main effect of trial pair, $F(2,40) = 9.57$, $p < .001$. The second analysis was a 2 (condition: experimental [$n = 12$] vs. baseline [$n = 6$]) × 3 (trial pair) × 2 (test display) mixed-factor ANOVA. This analysis revealed the same two effects: a condition × test display interaction, $F(1,16) = 12.05$, $p < .005$, and a main effect of trial pair, $F(2,32) =$

7.68, $p < .005$. Both analyses indicated that the infants in the experimental condition showed a greater looking preference for the separated display than did the infants in the baseline condition, and that the infants in both conditions showed a decline in looking time over the test sequence.

Comparisons of Experiments 1 and 2.—To examine further the effects of figural goodness on infants' perception of objects, the habituation and test trial data of the infants in the two experiments were compared. Concerning the haptic habituation period, no differences were found between the two experiments in holding time on the first three trials, number of trials to habituation, or total holding time, all t's < 1. For the visual test, only the data from the experimental conditions were analyzed because the baseline preferences between the connected and the separated test displays did not differ across the experiments, $t(22) < 1$. Test trial looking times were analyzed by a 2 (condition: experiments 1 vs. 2) × 2 (test order) × 3 (trial pair) × 2 (test display) mixed-factor ANOVA. This analysis revealed main effects of trial pair, $F(2,40) = 7.76$, $p < .001$, and of test display, $F(1,20) = 16.82$, $p < .001$: Infants looked longer on the earlier trials, and they looked longer at the separated display. No main effects or interactions involving condition approached significance: Looking preferences did not differ across the two experiments.

Discussion

After habituating to two rigidly movable rings that differed in substance, weight, texture, and shape, infants looked longer at a display in which the two rings were presented as distinct objects than at a display in which the two rings constituted the ends of a single, connected object. This looking preference was not due to a baseline effect. It provides evidence that the infants perceived the two rigidly movable rings as one connected body. A comparison with Experiment 1 suggested that this preference was as strong as in the first experiment, in which infants felt two rings of the same substance, weight, and texture that together formed a simple shape. Haptic perception of object unity does not appear to be affected by figural goodness.

Why did figural goodness fail to influence perception in these experiments? One possibility is that the infants in these experiments failed to detect or attend to the shape and substance properties of the rings they held. The next experiment addressed this possibility.

Experiment 3

A variety of experiments provide evidence that young infants are sensitive to the properties of the objects they feel. In particular, infants have been shown to discriminate orally or manually between objects of different shapes (Streri, 1987; Streri & Pêcheux, 1986a, 1986b), substances (Gibson & Walker, 1984; Rochat, 1987), and textures (Meltzoff & Borton, 1979). When infants hold the two ends of a rigid object with two hands, however, they may attend only to the common motion of the object. Thus, infants may fail to perceive the shapes, substances, textures, and weights of the ends they hold. This failure of perception could account for the absence of an effect of figural goodness on haptic object perception.

Experiment 3 investigated this possibility. The experiment used the haptic habituation and haptic discrimination method of Streri and Spelke (1988, Experiment 1). Separate groups of 4-month-old infants were habituated to each of the four ring assemblies from Experiments 1 and 2, following the same habituation method as those experiments. After habituation, the infants were tested with a second ring assembly from those experiments: an assembly in which one of the rings was the same as the corresponding ring in the first assembly but in which the other ring was different. The first and second ring assemblies were presented in alternation on six haptic test trials. If infants could perceive and discriminate between the rigid and flexible rings under the conditions of Experiments 1 and 2, they were expected to explore the new ring assembly longer than the assembly to which they were habituated.

Method

Subjects.—Participants were 16 infants, six boys and 10 girls, residing in Paris. They ranged in age from 3 months, 10 days to 4 months, 19 days (mean age, 4 months, 0 days). Eight additional infants were eliminated from the sample because of fussiness (7) or technical failures (1).

Displays and apparatus.—The displays for both the habituation and the test periods were the same ring assemblies as were used for the habituation periods of Experiments 1 and 2. The apparatus was also the same.

Design.—Eight infants were habituated to one of the ring assemblies from Experiment 1: two rigidly connected rings of the same substance, weight, texture, and shape. For half the infants, these were the rigid rings; for the others, these were the flexible rings. The remaining eight infants were habituated to one of the ring assemblies from Experiment 2: two rigidly connected rings of different substances, weights, textures, and shapes. The rigid ring was presented to the left hand for half these infants and to the right hand for the other infants. All the infants were tested with the ring assembly presented for habituation, and also with a second ring assembly from Experiment 1 or 2, in which just one of the rings differed from that of the first assembly. The location of the different ring (left hand vs. right hand) and the order of presentation of the two test displays (familiar assembly first vs. novel assembly first) were orthogonally counterbalanced within each habituation condition.

Across the experiment, each of the ring assemblies served equally often as the familiar and as the novel test display. Differences in the intrinsic attractiveness of the different assemblies therefore could not affect holding preferences between the familiar and novel display, and no baseline condition was needed for this experiment.

Procedure.—The habituation procedure was the same as for Experiments 1 and 2. The procedure for each of the six haptic test trials was the same as the habituation trial procedure: An experimenter placed a ring assembly in the infant's hands, beginning the trial, the trial continued until the infant dropped one or both rings, and then the experimenter removed that ring assembly and placed the other assembly in the infant's hands. Habituation trial holding times were recalculated from the video record by the first experimenter to determine whether the criterion of habituation had been calculated correctly; it was found to be correct, for every subject. Test trial holding times were recalculated from the video record by the two experimenters working together. The experimenters coded the test trials without observing the habituation trials, and thus they did not know which of the two test displays was familiar and which was novel for each subject. A separate pair of observers coded the haptic test trials for six infants; interobserver agreement averaged .98.

Results

Habituation period.—Preliminary analyses revealed no differences in habituation characteristics between the infants habituated to two rigid rings and those habituated to two flexible rings, all t's$(6) < 1$. Preliminary analyses also revealed no differences in habituation characteristics between the infants habituated to a rigid ring in the left hand and a flexible ring in the right hand and those for whom the left- and right-hand rings were reversed, all t's$(6) < 1.7$, $p > .10$. Accordingly, the eight infants who were habituated to identical rings (both rigid or both flexible) were considered as a single group, as were the eight infants who were habituated to nonidentical rings (rigid right or rigid left).

Characteristics of the habituation phase appear in Table 1*c* and Figure 5. The infants who were habituated to nonidentical rings appeared to explore them longer than those who were habituated to identical rings. This difference, however, was not significant on any measure, all t's$(14) < 1.7$, $p > .10$. All subjects met the criterion of habituation within 15 trials.

Test period.—Preliminary analyses revealed no effect of the location of the new ring (left hand vs. right hand) or of the order of test trials (new assembly first vs. old assembly first) on the magnitude of the holding-time preference for the novel ring assembly, both t's$(14) < 1$. Preliminary analyses also revealed no difference in test preferences, within the identical rings condition, between the infants habituated to rigid versus flexible rings, $t(6) < 1$, and no difference in test preferences, within the nonidentical rings condition, between the infants habituated to the rigid ring in the left hand versus the rigid ring in the right hand, $t(6) = 1.48$, $p > .10$. Accordingly, these factors were not considered further.

Figure 5 presents the test trial holding times for the infants habituated to an assembly of identical rings and for the infants habituated to an assembly of nonidentical rings. The infants in both conditions tended to hold the novel rings longer than the familiar rings on all pairs of test trials. This preference was observed for seven of eight subjects presented with a new ring in the left hand and for eight of eight subjects presented with a new ring in the right hand (each $p < .05$ or better, sign test). Test trial holding times were subjected to a 2 (condition: identical rings vs. nonidentical rings) × 2 (test display: familiar vs. novel) × 3 (trial pair) ANOVA with the last two factors within subjects. This analysis revealed a significant effect of test display, $F(1,14) = 5.25$, $p < .05$: Infants held the novel ring assembly longer than the familiar ring assembly. The only other significant factor was a main effect of condition, $F(1,14) = 5.87$, $p < .05$: Test trial holding times were longer, in general, for the infants habituated to an assembly of nonidentical rings than for the in-

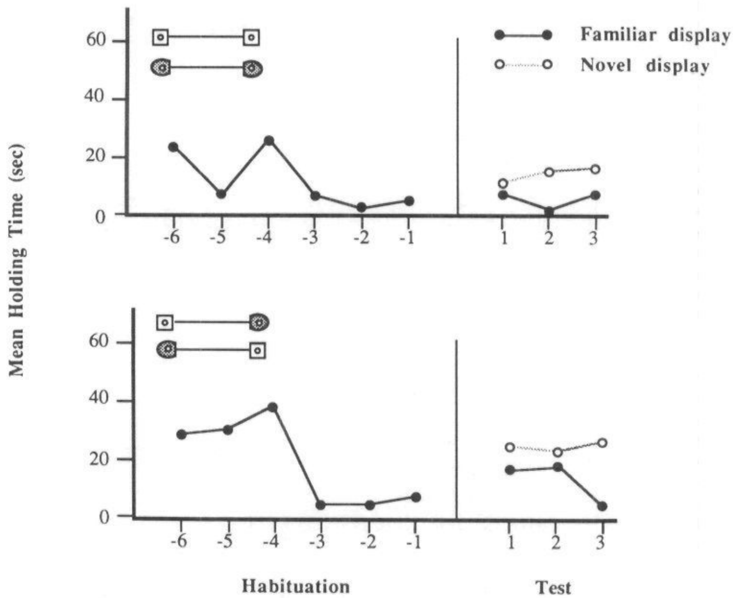

FIG. 5.—Holding times for familiar and novel ring displays after haptic habituation to rings united by common motion and figural goodness (top) or after habituation to rings united by common motion but not by figural goodness (bottom).

fants habituated to an assembly of identical rings.

Discussion

Experiment 3 provides evidence that 4-month-old infants can discriminate between the rigid and flexible rings used in Experiments 1 and 2. Infants detected a change in rings in either the left or the right hand, even though both hands held rings that moved rigidly together, and even though only one of the hands held a novel ring during the test. Infants evidently can detect the shape and/or substance properties of objects when they hold two objects that move rigidly together. Moreover, infants attend to and remember one or more of these properties sufficiently to dishabituate to a change in them. The failure of infants to use shape or substance properties to specify object boundaries does not appear to stem from limits on sensitivity, attention, or memory.

During both the habituation and the test period, the infants who were habituated to an assembly of nonidentical rings held all the ring assemblies longer than those who were habituated to an assembly of identical rings. This difference was not obtained in Experiments 1 and 2, however, and will not be discussed further.

Experiment 4

The final experiment investigated whether shape and substance properties influence haptic object perception for adults, in accord with the gestalt principles of similarity and good form. Adult subjects were allowed to feel, but not see, enlarged versions of the four ring assemblies presented to infants. The subjects were asked to hold the rings as young infants do, grasping and displacing them but not engaging in finger movements that could bring their hands into further contact with the displays. Perception of the unity or separateness of the rings was assessed by asking the subjects (1) whether the rings appeared to be connected or not connected to each other, and (2) whether the rings appeared to form a single object or two distinct objects.

Method

Subjects.—Participants were 12 volunteers residing in or near Ithaca, NY. The six male and six female subjects ranged in age from 17 years to 31 years (mean age, 21.5 years). Subjects were recruited by signs posted near the Cornell Infant Research Center. They were paid for their participation.

Displays and apparatus.—The haptic displays were the same as those of Experiments 1 and 2 on all dimensions except size. To permit the adult subjects to manipulate the ring assemblies as did the infants, the size of all the displays was increased by 150%. The displays were made of the same materials as those used with infants.

Subjects were tested in a seated position, facing a white wall with white shelves. A patterned cloth was tied around a subject's neck at one end and attached at the other end to the wall appproximately at eye level. The cloth blocked the subject's view of his or her body and of the haptic displays. The shelf immediately above this cloth contained a 7-point cardboard scale with the points labeled "1 (weak)" to "7 (strong)."

Design.—Each subject was presented haptically with four ring assemblies: two rigid rings, two flexible rings, a rigid left-hand ring and flexible right-hand ring, and a rigid right-hand ring and flexible left-hand ring. Each ring assembly was presented in each ordinal position for equal numbers of subjects: identical rings and nonidentical rings were presented to each subject in an ABBA (or BAAB) order.

Procedure.—Subjects were run individually by the personnel of the Cornell Infant Research Center in one of the center's experiment rooms. A subject was told that the experiment was designed to investigate "how adults perceive some of the displays we present to infants." Then the subject was seated in the experiment room, the cloth was tied around his or her neck, and the following instructions were read: "I am going to give you four displays to feel. These will be unfamiliar and will have no meaning for you. Please hold each display exactly the way that I give it to you: do not move your hands over the display to feel any part I don't have you feel when I first put the display in your hands. This may sound strange, but when we put something into a young baby's hands, the baby does not usually move her fingers around it, and we want to see what adults will perceive under the same conditions.[5] While you hold the display, I will ask you if what you are holding in your left hand feels connected to what you are holding in your right hand or not."

The experimenter then placed the first ring assembly in the subject's hands, allowed the subject to explore the rings for about 5 sec, and asked, "Is this connected or not connected?" After the subject answered this question, the experimenter pointed to the 7-point scale and continued: "Please rate the strength of this impression, with '1' being a very weak impression of [connectedness/separateness], and '7' being a very strong impression of [connectedness/separateness]."

Following this judgment, the subject was given the following additional instructions: "When we feel things with both hands at once, sometimes we have the impression we are feeling two distinct objects, one in each hand, and sometimes we have the impression that we are feeling one object with both hands. For example, if I gave you two tennis balls, one in your left hand and one in your right, you would perceive two distinct objects; if I put one beach ball between your two hands, so that one hand held each side of the ball, you would perceive one object. Unlike tennis balls and beach balls, what you will hold now should not feel familiar or meaningful. Still, I'd like you to tell me whether what you're holding feels like one object or two objects to you."

After the subject answered this question, the experimenter again pointed to the scale and continued: "Please rate the strength of this impression, where '1' is a very weak impression that you are holding [one object/two objects], and '7' is a very strong impression that you are holding [one object/two objects]."

After the rating was given, the ring assembly was removed, the next ring assembly was presented, and the questions were repeated. This procedure was followed for all four ring assemblies.

All subjects' responses were written down by a second experimenter, who sat below the cloth, out of view. That experimenter also monitored the subject's hand movements to determine if the subject followed the instructions not to touch the center of the display. One subject touched the center and was replaced.

Measures and analyses.—For purposes of analysis, each connectedness judgment was given a score from -7 (strong impression of separateness) to $+7$ (strong impression of connectedness), and each number-of-objects judgment was given a score from -7 (strong impression of two objects) to $+7$ (strong impression of one object). The 12 scores for each display and each judgment were tested against the neutral value of 0 by two-tailed t tests. (The tests were two-tailed because no predictions had been made concerning the

[5] Pilot testing revealed that in the absence of this instruction, subjects tended to finger the rings actively and to touch the central bar—a pattern rarely seen with 4-month-old infants (see Hatwell, 1986, and n. 3).

TABLE 2

ADULTS' JUDGMENTS OF OBJECT CONNECTEDNESS AND OBJECT UNITY

	Connectedness Judgments	Unity Judgments
Rigid rings	6.67 (.52)	6.33 (.80)
Flexible rings	6.58 (.80)	5.50 (3.42)
Rigid right	5.58 (2.20)	2.42 (5.07)
Rigid left	5.92 (1.09)	2.92 (4.96)

NOTE.—The table gives the means (and standard deviations) for each judgment of each display.

judgments for the displays of nonidentical rings.) One-tailed t tests then compared judgments for the identical ring displays to judgments for the nonidentical ring displays in order to test the prediction that connectedness judgments and one-object judgments would be higher for the identical ring displays.

Results

Judgments of connectedness.—The mean connectedness judgments for each display are given in Table 2. All four displays were judged to be connected, all t's$(11) \geq 8.43$, $p < .001$. Eleven of the 12 subjects reported that all the ring assemblies were connected; the twelfth subject reported (with a low strength-of-impression rating) that one of the assemblies of nonidentical rings was not connected. Further analyses revealed no difference between the connectedness judgments for the two identical ring displays ($t < 1$) and no difference between the connectedness judgments for the two nonidentical ring displays ($t < 1$). Accordingly, each subject's judgments for the two identical ring displays were added together and compared to his or her summed judgments for the two nonidentical ring displays. These judgments differed significantly, $t(11) = 4.39$, $p < .001$. Nine subjects reported a stronger impression of connectedness for the identical ring displays than for the nonidentical ring displays, and the remaining three subjects reported equally strong impressions for the two types of displays ($p < .002$, sign test).

Judgments of object number.—The mean number judgments for each display are given in Table 2. Although it appears that all the displays were judged to consist of one object, this judgment was only significant for the two assemblies of identical rings, $t(11) = 26.32$ for the rigid rings and $t(11) = 5.34$ for the flexible rings, both p's $< .001$. Judgments for the nonidentical rings did not differ significantly from the neutral point of zero, $t(11) = 1.58$, $p < .20$, for the rigid-left assembly and $t(11) = 1.95$, $p < .10$, for the rigid-right assembly. Seven of the 12 subjects reported that all the ring displays consisted of one object. The remaining subjects reported that one nonidentical ring display ($n = 3$), both nonidentical ring displays ($n = 1$), or both nonidentical ring displays and one identical ring display ($n = 1$) consisted of two objects.

Further analyses revealed no difference between the number judgments for the two assemblies of identical rings ($t < 1$) or between the number judgments for the two assemblies of nonidentical rings ($t < 1$). Accordingly, judgments for the two identical ring assemblies were summed and compared to the summed judgments for the two nonidentical ring assemblies. These judgments differed significantly, $t(11) = 3.51$, $p < .01$. Eleven subjects reported a stronger impression of one object for the identical ring displays than for the nonidentical ring displays, and one subject reported equally strong impressions for the two types of display ($p < .001$, sign test).

Discussion

When adult subjects manipulated ring displays similar to those of Experiments 1 and 2, their perception of object unity and connectedness appeared to be influenced both by common motion and by figural goodness. Adults tended to report that all the ring assemblies consisted of one connected object, as they should if rigid motion influences perceived connectedness and perceived object unity. The adults' judgments of connectedness and of object unity were reliably stronger, however, when the rigidly movable rings were uniform in shape and substance than when they were not. For touch as for vision (e.g., Koffka, 1935; Wertheimer, 1958; Kellman & Spelke, 1983), figural goodness appears to influence adults' perception of objects.

Although the effects of figural goodness on connectedness judgments and unity judgments were highly consistent, they were small. Nearly all the subjects judged that the nonidentical ring assemblies were connected, and more than half the subjects judged that they consisted of one object. For this reason, the differences between the findings with infants and with adults should not be overemphasized. For adults and infants alike, haptic object perception appears to be influenced primarily by motion.

General Discussion

The present experiments provide further evidence that 4-month-old infants, like adults, can perceive objects through active touch. When infants hold two spatially separated but rigidly movable rings, they appear to perceive one connected object that extends between their hands. The experiments support Streri and Spelke's (1988) conclusion that common, rigid motion specifies object unity to young infants in the haptic mode, as it does in the visual mode.

Experiments 1 and 2 suggest that 4-month-old infants fail to perceive the connectedness of two haptically explored object parts by analyzing the sameness of their substances or the simplicity of their combined shape. Although infants were able to discriminate haptically between rings that differed in substance, weight, texture, and shape, infants perceived the connectedness of two rigidly movable rings just as strongly when the rings differed on those dimensions as when the rings were the same on those dimensions. In the haptic mode as in the visual mode, young infants do not appear to perceive objects by maximizing figural goodness.

These findings suggest that figural goodness begins to influence object perception after 4 months of age. Neither for touch nor for vision, moreover, does this development appear to depend on the development of abilities to discriminate the shape and substance properties of objects. The convergence of findings from studies of object perception in the haptic and the visual modalities suggests that amodal mechanisms serve to organize the surface layout into objects. The mechanisms of object perception appear to operate on relatively central representations of surfaces and their motions, regardless of the input system from which a representation of surfaces was derived. This finding is consistent with the findings of several recent investigations of visual object perception in infancy (Kellman et al., 1987; Spelke et al., 1989; see Spelke, 1988).

Although the present findings provide evidence for an amodal mechanism of object perception, the evidence is not fully conclusive: Object perception could depend on separate, modality-specific mechanisms that happen to succeed and fail under the same conditions at 4 months of age. Studies of the subsequent development of object perception might permit a more decisive test of the amodal mechanism hypothesis. If object perception depends on a single, central mechanism, then figural goodness should begin to influence object perception in the haptic mode at the same time in development that it begins to influence object perception in the visual mode. Developmental changes in perception of visible objects are just beginning to be studied (Schmidt, 1985; Schmidt et al., 1986). As more is learned about this development and about developmental changes in haptic perception, the stronger test may become feasible.

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