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Haptic Perception of Objects in Infancy

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Four-month-old infants held two rings, one in each hand, out of the field of view. In one condition, the rings could be moved independently; in the other condition, the rings could only be moved rigidly together. After exploring the rings haptically, infants received a haptic or visual test with pairs of rings that were connected or separated. The findings of four experiments provide evidence that infants explored the rings bimanually, producing patterns of rigid or independent motion, that infants discriminated between the two motion patterns, and that this discrimination transferred from touch to vision. Most importantly, the experiments provide evidence that infants perceived the unity and boundaries of objects by detecting the motion patterns they themselves produced. Infants who explored the independently movable rings perceived two distinct objects, whereas those who explored the rigidly movable rings perceived a single object that was connected between the two hands. Since the same motion patterns specify object boundaries in the visual mode, object perception may depend on a relatively central process.

When adults explore by touch, their hands move over surfaces and displace objects relative to one another, encountering only small parts of the layout at any given time. These fragmentary and changing encounters are organized into a unitary and stable world (Gibson, 1962): Adults perceive continuous, bounded, and enduring objects through their active ex-

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ploration. The present experiments begin to investigate the origins of this capacity. They focus on young infants' perception of objects explored with two hands.

Research on infancy presents a somewhat contradictory picture of the development of haptic perception. Evidence that visual perception develops rapidly in infancy (see Banks & Salapatek, 1983), coupled with longstanding observations that manual exploration develops slowly over childhood (see Gibson & Spelke, 1983), have overturned the traditional view that "touch teaches vision," and seem to invite the opposing view that manual exploration and haptic perception develop under visual guidance (Hatwell, 1986).

Recent experiments suggest, nevertheless, that young infants do explore and perceive objects manually. In one series of studies, infants were habituated to a rigid object held in one hand out of the field of vision, and then they were presented with a new object of a different form. Holding time increased reliably, at both 4½ months (Streri & Pêcheux, 1986a) and 2½ months (Streri, in press), indicating that the two forms were discriminated. In other experiments, 2- and 5-month-old infants were presented with a rigid object outside the visual field and were allowed to explore it spontaneously. Manual exploration was observed at all ages, and intermanual transfer began to occur by 4 months (Rochat, 1985). Since infants do not begin to reach for visible objects until well into the fifth month, these observations suggest that capacities to perceive by active manipulation are functional before the coordination of prehension and vision.

Given that young infants can discriminate object shapes haptically, it is reasonable to ask whether they can also perceive objects as unitary and bounded. The task of organizing the felt surface layout into objects is especially important, because the hands explore by displacing objects and manipulating them. This task is complex, however, for it requires that perceivers go beyond their immediate encounters with surfaces to discover the enduring and continuous layout that extends outside their grasp.

Recent research provides evidence that infants can and do go beyond their immediate encounters with surfaces when they are presented with objects in the visual mode. Infants perceive the unity and boundaries of objects in complex visual displays by detecting the common and the independent motions of surfaces. When two surfaces move rigidly together while standing partly hidden behind a common occluder, for example, the surfaces are perceived to lie on a single object that continues behind the occluder (Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986). When two sets of surfaces undergo separate motions while standing adjacent in depth, one partly hiding the other, they are perceived to lie on two distinct objects (Hofsten & Spelke, 1985; see also Spelke, Hofsten & Kestenbaum, 1986). Only the kinetic relationships among surfaces appear to influence infants' perception in these situations. In particular, young infants fail to perceive object boundaries by analyzing the static, configurational properties of the visible layout. Unlike adults and toddlers (Schmidt, 1985), infants do not organize surfaces into objects in accord with the gestalt principles of similarity, good continuation, and good form (Kellman & Spelke, 1983; Kestenbaum, Termine, & Spelke, in press; Schmidt & Spelke, 1984; Schmidt, Spelke, & LaMorte, 1986).

Guided by these findings, the present experiments investigated whether infants perceive the unity and boundaries of objects in the haptic mode, by producing and detecting patterns of common and independent surface motion. Infants held two sets of surfaces, one in each hand, outside the field of view. In one condition, the surfaces could be moved independently; in the other condition, they could only be moved in a rigid relation to one another. The experiments investigated whether the infants would perceive that the rigidly movable surfaces formed a single connected object, whereas the independently movable surfaces formed two separate objects.

These experiments were undertaken for a further reason, since studies of haptic perception in infancy may shed light on the mechanisms of object perception more generally. At present, it is not clear whether the organization of the world into objects depends on a collection of relatively peripheral mechanisms, each specific to a single perceptual system, or on a single mechanism that is more central. If object perception depends on separate visual and haptic mechanisms, then those mechanisms might begin to function at different times, and they might function initially in accord with different principles. If a central mechanism underlies object perception, in contrast, infants should begin to perceive objects haptically at the same age that they begin to perceive objects visually, provided that these achievements are not blocked by peripheral limits. Perception should follow the same principles, moreover, whether objects are seen or felt. In particular, 4-month-old infants should perceive objects haptically by detecting common and relative surface motions.

In 4 experiments, therefore, 4-month-old infants were presented with rigidly or independently movable ring-shaped objects. After a series of familiarization trials, infants were given a haptic discrimination test (Experiment 1), a visual transfer test with connected and separated rings undergoing their characteristic motions (Experiment 2), or a visual transfer test with connected and separated rings undergoing no distinctive motion (Experiments 3 and 4). The experiments addressed four questions. First, do young infants explore objects by displacing them actively, moving both hands so as to produce patterns of rigid or independent motion? Second, can young infants discriminate these bimanually produced motion patterns? Third, do young infants recognize visually the commonly or independently movable surfaces they have felt? Fourth, do young infants perceive the unity and boundaries of objects by detecting the motion patterns they produce? When an infant can move two rings independently, does she perceive each ring as a separate, bounded object? When she holds two rings that can only be moved rigidly together, does she perceive one connected object that extends between her hands?

EXPERIMENT 1: HAPTIC DISCRIMINATION

Method

Subjects. Participants were 24 healthy, normal infants—15 boys and 9 girls—residing in Paris. The infants ranged in age from 3 months, 26 days to 4 months, 29 days (mean age, 4 months, 15 days).

Displays and apparatus. The apparatus is depicted in Fig. 1. Each infant sat in a semireclining canvas seat facing a three-sided white enclosure, 80 cm high and 50 cm long, that shielded the infant from the surrounding experimental room. A white cloth, tied at one end to the infant seat and at the other end to a position at the baby's eye level on the front panel of the enclosure, blocked the baby's view of his body without limiting his range of movement. The infant's hands and body could be observed through a video camera placed behind a hole in the front panel, 1 cm below the cloth.

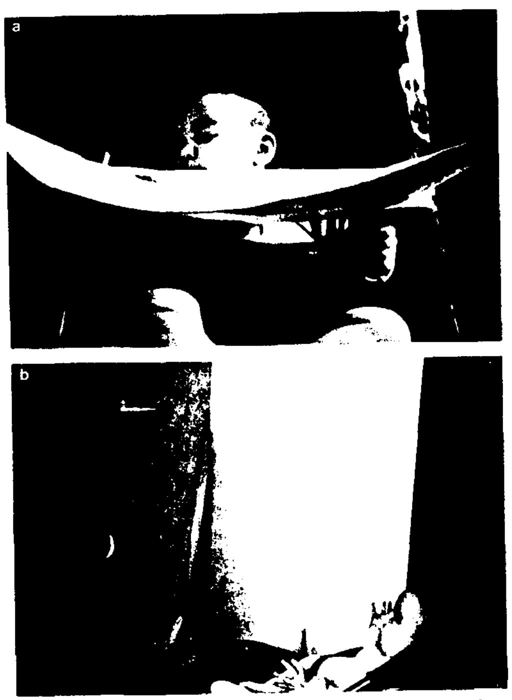

FIG. 1. The experimental apparatus: (a) on haptic familiarization trials, viewed from the position of the video camera; (b) on visual test trials, with the connected ring display from Experiment 3.

The objects were two wooden rings, 45 mm in diameter and 8 mm thick, connected by a thin 150-mm wooden bar or by a highly flexible 150-mm elastic band (Fig. 2). When an infant held one ring in each hand, he could not normally feel the bar or band that connected them (see below). The rings connected by the bar moved rigidly together when the infant attempted to displace them. The rings connected by the band moved independently unless the infant extended his arms and pulled them in opposite directions.

Design. Equal numbers of infants were habituated to the rigidly and the independently movable rings. All the infants then received 6 test trials in which the rigidly and the independently movable rings were presented in alternation. The order of test trials was counterbalanced across infants in each habituation group.

Procedure. After the infant was seated, the cloth was tied over his body and the experiment began. An experimenter, seated behind and to the right of the infant, placed the two rings in the infant's hands, and then a second experimenter observed the infant's activity on the video monitor. The infant was allowed to manipulate the two rings at will. When he released a ring, after holding both rings for at least 1 s, the second experimenter signaled the end of the trial to the first experimenter, who removed the other ring and then presented the two rings anew, beginning the second trial. A trial was also ended after 90 s of continuous holding. Trials were continued until 15 trials had been 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 trials for which holding time equaled or exceeded 30 s. Each infant therefore received between 6 and 15 habituation trials. After habituation, the test trials began immediately, following the same procedure as the habituation trials.

During the experiment, the second experimenter recorded the duration of holding time per trial and determined when the habituation criterion was met. These holding times were

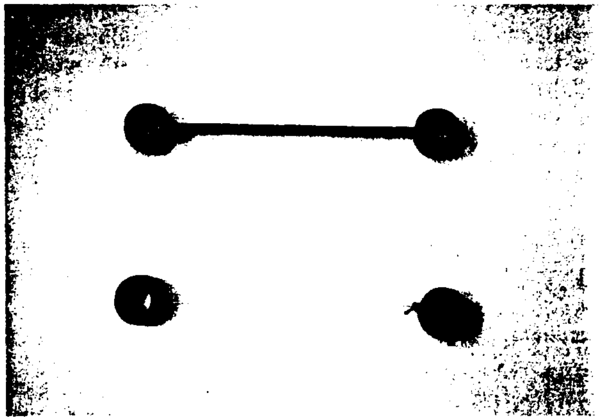

FIG. 2. The stimulus objects.

later recalculated from the video record by the first experimenter. The principal dependent measure was the duration of holding time on each test trial. Test trial holding times were coded from the video record by the first and second experimenters working together. During this coding, the experimenters did not view the habituation period and were blind to the experimental condition of each baby. To determine the reliability of test trial coding, six randomly chosen subjects from each condition were coded by two additional observers, working together in ignorance both of a baby's experimental condition and of the purpose of the experiment. The reliability between the two pairs of observers, for these 12 infants, was high, $r = .99$.

Results

Habituation period. The infants in both familiarization conditions explored the rings for extended periods of time. All the babies met the criterion of habituation within 15 trials. There was no difference between the two conditions with respect to total exploration time, number of trials to the criterion of habituation, or total holding time on the first 3 trials (see Table 1 and Fig. 3). Inspection of the videotapes suggested, nevertheless, that infants explored the rigidly and independently movable rings somewhat differently. For infants in the rigid motion condition, both hands moved at once, such that the ring display underwent a rotary or translatory motion; for those in the independent motion condition, the hands tended to move in alternation, one hand resting while the other displaced a ring. Infants released the displays with the right hand on 66 trials, with the left hand on 80 trials, and with both hands on 10 trials. They touched the wooden or elastic connection between the rings on 11 of 183 trials (6%). Eighteen of the twenty-four subjects never touched this connection.

Test period. Mean holding times during the test trials are presented in Fig. 3. Infants who were habituated to the rigidly movable rings explored the independently movable rings longer than the rigidly movable rings during the test; infants habituated to the independently movable rings showed a slight tendency in the opposite direction. The proportion of time spent holding the independently movable rings was calculated for each infant and each pair of test trials by dividing the holding time for the independently movable rings by the sum of the holding times for the

TABLE 1
Characteristics of Habituation, Experiment 1

	Object motion		
	Rigid	Independent	$t(23)$
Holding, first 3 trials (s)	95.0	95.0	<1
Trials (No.)	7.2	7.4	<1
Total holding time (s)	142.7	169.9	<1

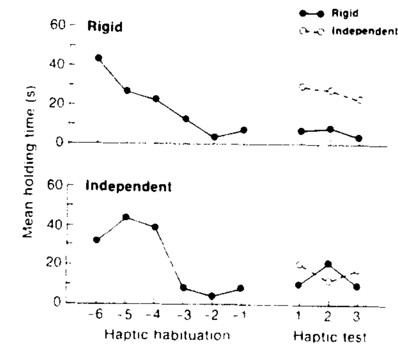

FIG. 3. Holding times in Experiment 1 by infants familiarized with rigidly or independently movable objects.

rigidly and the independently movable rings. A 2 (Habituation condition) × 2 (Test trial order) × 3 (Test trial pair) ANOVA on these proportion scores revealed a significant effect of condition, $F(1,20) = 9.30$, $p < .01$: Proportion of holding time for the independently movable rings was .695 in the rigid motion condition and .490 in the independent motion condition. No other main effects or interactions were significant.[1]

The test preference for the novel rings was no stronger for the 6 infants who had touched the connection between the rings than for the 18 infants who had not. For infants who had touched the center—all in the rigid motion condition—the proportion of time devoted to the novel, independently movable rings averaged .714; for the remaining 6 infants in this condition, the proportion averaged .710. If the infants who touched the center were removed from the sample, the preference for the novel test display (.574) is marginally greater than .5, $t(17) = 1.61$, $p < .1$, one-tailed.[2]

Discussion

The present experiment provides evidence that 4-month-old infants explore objects bimanually by grasping and then displacing them. In gen-

[1] In addition to the analysis of proportion scores, analyses of raw and log-transformed looking times were performed. Both revealed a significant interaction of Condition × Test display (rigid vs independent motion): For raw times, $F(1,20) = 4.48$, $p < .05$; for logs, $F(1,20) = 8.35$, $p < .01$. These effects corroborate the proportions analysis. In addition, both analyses revealed a main effect of Test display: Infants explored the independently movable rings longer than the rigidly movable rings.

[2] The use of .5 as the chance value is conservative. In this analysis, the novel display was the rigid motion display for 12 of the 18 subjects, and that display was explored less, in general, than the other display.

eral, infants did not attempt to explore the objects by running their fingers over their surfaces: only 6 infants ever touched the part of the display which they were not given to grasp. Infants did displace the objects actively, however, moving the rigidly connected rings together and the other rings independently.

The present experiment also provides evidence that infants discriminate rigidly and independently movable objects. Preferences between the test displays were influenced by the prior period of habituation: Infants who had been habituated to the rigidly movable rings tended to hold the independently movable rings longer than those who had been habituated to the independently movable rings. Since the displays were composed of identical rings, infants could not have discriminated them by detecting object properties that could be felt by one hand. Rather, infants detected the relationship between the motions of the objects in the two hands, and they discriminated the two patterns of bimanual movement. The next experiment investigated whether infants who have manipulated these displays will recognize them in the visual mode.

EXPERIMENT 2: HAPTIC-TO-VISUAL TRANSFER

Infants were habituated to the rigidly or independently movable rings, as in Experiment 1, and then they were given a series of visual test trials. The cloth was removed and infants were allowed to look at the connected and separated ring displays, each undergoing its characteristic motion. Infants were expected to look longer at the ring display that differed from the display they had manipulated.

Method

The method was the same as in Experiment 1, except as follows.

Subjects. The 16 participants (10 boys and 6 girls) ranged in age from 3 months, 25 days to 4 months, 29 days (mean age, 4 months, 11 days). One additional infant was rejected from the sample because of experimenter error in calculating the criterion of habituation.

Displays and apparatus. During the visual test, the white cloth was removed and infants viewed pairs of red wooden rings against the front panel of the enclosure (Fig. 1b). These rings were identical in size, shape, and material to those presented haptically. At their distance of 40 cm from the baby, each ring subtended 6°. The two rings in each display were suspended from the top of the front panel by white 21-cm strings attached to a horizontal white rod. The rings were 15 cm apart in both displays. In one display, the rings were connected by the wooden bar, which was painted red. In the other display, the rings were connected by the elastic band, which was white. Against the white background, neither the strings nor the band were easily visible by adults. The rod holding the strings was visible but inconspicuous. Just before each trial began, the rod was struck briefly by the experimenter's hand, causing the rings to jiggle. For the rings connected by the bar, the entire display moved rigidly; for the rings connected by the elastic, the two rings moved with relative independence.[3] A white screen held in front of the display panel blocked the infant's view of the rings (and of the hand that agitated them) between trials.

Design. Equal numbers of infants were habituated haptically to the rigidly and the independently movable rings. All the infants then received 6 visual test trials in which the connected, rigidly moving rings and the separated, nonrigidly moving rings were presented in alternation. The order of presentation of the two test displays was counterbalanced across the infants in each habituation group.

Procedure. The habituation procedure was the same as in Experiment 1. After the last habituation trial, the white cloth was removed to reveal the entire enclosure with the screen covering the visual display. The second experimenter positioned a ring display behind the screen and jiggled it. Once the display began to move, the first experimenter lifted the screen and the test trial began. Each visual test trial continued until the baby had looked away for 2 s, after looking at the display for at least 1 s. At the end of a 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.

Holding times during the habituation period were later recalculated from the video record by the first experimenter. On the basis of her calculations, it was determined that one subject had not met the criterion of habituation. This subject was replaced. Test trial looking times were coded from the video record by both experimenters working together, in ignorance of the experimental condition of the baby. A separate pair of experimentally naive obervers also coded the looking times of 8 randomly chosen subjects, 4 in each condition. Reliability between the two pairs of observers was moderately high, $r = .90$.

Results

Habituation period. Characteristics of the habituation phase are presented in Table 2 and Fig. 4. Infants tended to explore the independently movable rings longer than the rigidly movable rings, and they habituated to the former display in somewhat fewer trials. All the infants met the criterion of habituation within the alotted 15 trials. Infants touched the central connection between the rings on 6 of 138 habituation trials (4%); 2 infants in each condition touched the center.

TABLE 2
Characteristics of Habituation, Experiment 2

	Object motion		
	Rigid	Independent	$t(15)$
Holding, first 3 trials (s)	73.0	123.5	1.95*
Trials (No.)	9.6	7.7	1.59
Total holding time (s)	159.1	241.1	1.73

* $p < .1$, two-tailed.

[3] It is possible that the movements of the rings in this display were somewhat correlated, since the rings were yoked by the elastic band.

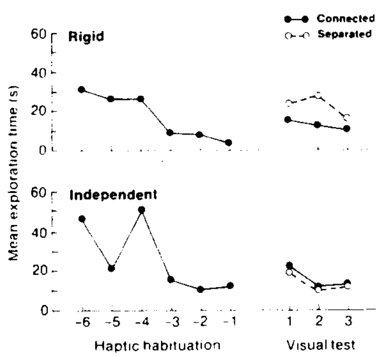

FIG. 4. Holding times and looking times in Experiment 2 by infants familiarized with rigidly or independently movable objects.

Test period. Test trial looking times are presented in Fig. 4. After habituating to the rigidly movable rings, infants looked longer at the separated, nonrigidly moving rings: after habituation to the independently movable rings, infants showed a weak preference for the connected, rigidly moving rings. A 2 (Habituation condition) × 2 (Order) × 3 (Test trial pair) ANOVA on the proportion of looking time to the separated, nonrigidly moving rings revealed a main effect of Condition, $F(1,12) = 8.19$, $p < .02$: The proportion of looking at the separated rings averaged .575 for infants in the rigid motion condition and .462 for infants in the independent motion condition. There were no other significant effects.[4]

For the 2 infants in each condition who had touched the center of the habituation display, the proportion of looking at the novel visual display (i.e., the separated rings for infants in the rigid motion condition and the connected rings for those in the independent motion condition) averaged .543. This proportion averaged .558 for the 12 infants who had not touched the center, a preference that exceeded the chance value of .5, $t(11) = 2.24$, $p < .025$, one-tailed.

Discussion

Experiment 2 provides evidence that the discrimination between rigidly and independently movable rings transferred from touch to vision.

[4] The analysis of raw looking times revealed the predicted interaction of Condition × Test display, $F(2,18) = 8.15$, $p < .005$, and no other significant effects. The analysis of log-transformed looking times revealed a main effect of Test pair, $F(2,36) = 3.77$, $p < .05$, indicating that looking time declined over successive test trials, and the quadruple interaction of Condition, Order, Test pair, and Test display, $F(4,36) = 2.65$, $p < .05$. The predicted interaction of Condition × Test display was marginally significant, $F(2,18) = 3.47$, $p < .06$.

Infants who had explored the rigidly movable rings looked longer at the pair of rings that were connected only by elastic and that moved independently: infants who had explored the independently movable rings looked longer at the pair of rings that were connected by the bar and that moved rigidly together. Discrimination and transfer did not depend on any properties of a ring display that could be perceived by one hand, since the rings themselves were identical in the two displays. Discrimination and transfer also did not depend on touching the center of a ring display, since the same results were obtained when infants who touched the center were excluded. Infants evidently perceived bimanually the patterns of rigid and independent motion, and this perception served, in some way, as the basis for the visual transfer.

During the test, the rigidly moving rings were visibly connected and the independently moving rings were visibly separated, except for the elastic. It is possible that the observed visual preferences depended on infants' prior haptic perception of the two rings as connected in one condition and separated in the other. The experimental findings do not warrant this conclusion, however, because visual transfer may have depended solely on the detection of relatively familiar and novel patterns of motion. Experiments 3 and 4 focused directly on infants' perception of the connectedness or separateness of the rings, in order to investigate whether bimanually produced motion patterns provide information about object unity and boundaries.

EXPERIMENTS 3 AND 4: HAPTIC PERCEPTION OF OBJECTS

In Experiment 3, infants were habituated haptically to the rigidly or the independently movable rings and then were tested visually with rings that were connected or separated. The rings in both test displays underwent the same motion: a smooth, horizontal displacement. Infants could only differentiate the test displays, therefore, by detecting the presence or absence of a visible connection between the rings.

If infants perceive objects haptically by detecting surface motions, the infants who had manipulated the rigidly movable rings should have looked longer at the separated rings, whereas those who had manipulated the independently movable rings should have looked longer at the connected rings. This hypothesis was tested by comparing test trial looking patterns of infants in the two familiarization conditions to each other, and also by comparing test trial looking patterns of infants in each familiarization condition to those of infants in a baseline condition, in which the same visual test trials were preceded by no haptic familiarization

Method

The method was the same as for Experiment 2, except as follows.

Subjects. The 24 participants (16 boys and 8 girls) ranged in age from 3 months, 25 days to 5 months, 8 days (mean age, 4 months, 10 days). No baby was rejected from the sample.

Displays and apparatus. During the test trials, infants were presented with pairs of rings that were rigidly attached to a white, 40 × 25-cm board, suspended from the front panel such that the rings appeared in the same position, at the same distance from the baby, as in Experiment 2. The board was visible to adult observers, but it was inconspicuous against the white background. This board and the rings it supported underwent a steady, horizontal displacement, moving 20 cm to the left and right of center at the approximate rate of 20 cm (28°)/s. It was moved manually, from behind the display, by a fully concealed experimenter. The two pairs of rings differed only with respect to the presence vs absence of a visible connection between them: They were connected by the red bar in one display, and they were not connected in the other display. The rings were 15 cm apart in each display.

Design. Eight infants were haptically familiarized with the rigidly movable rings, 8 were familiarized with the independently movable rings, and 8 were given no period of familiarization. All the infants then received 6 visual test trials. The connected and separated rings were presented in alternation, with order counterbalanced within each habituation group.

Procedure. During the visual test trials each ring display was displaced rigidly by the second experimenter. She lowered the board into its position at the beginning of each test trial and then moved it back and forth, holding onto handles that were attached to the back of the board. At the end of the trial, she raised and removed the board. No screen was used.

Looking times of all subjects were coded from the video record by one pair of observers working together, and looking times of a subset of 12 subjects, 4 in each condition, were also coded by a second pair of observers. The agreement between the two pairs of observers, for this subset of infants, was moderately high, $r = .87$. All observers were blind to the expermental condition of each baby.

Results

Habituation period. Table 3 and Fig. 5 present the principal characteristics of the habituation phase. All the infants met the habituation criterion within 15 trials. Infants tended to explore the independently movable rings longer than the rigidly movable rings. Three infants, all in the rigid motion condition, touched the central connection between the rings on a total of 6 of 174 trials (3%).

Test period. Test trial looking times are presented in Fig. 5. The infants in the two experimental conditions showed long looking times on the first pair of trials, with a preference in both conditions for the separated ring display. On the remaining trials, those who had explored the rigidly movable rings looked longer at the separated rings, whereas those who had explored the independently movable rings did the reverse. The infants in the baseline group looked about equally at the two test displays.

TABLE 3
Characteristics of Habituation, Experiment 3

	Object motion		
	Rigid	Independent	$t(15)$
Holding, first 3 trials (s)	58.2	95.0	1.50
Trials (No.)	7.1	7.8	<1
Total holding time (s)	95.6	165.2	2.24*

* $p < .05$, two-tailed.

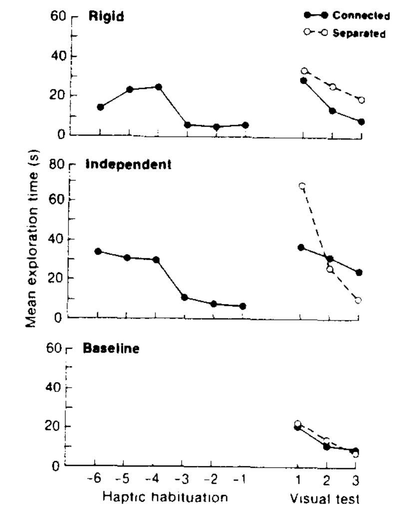

FIG. 5. Holding times and looking times in Experiment 3 by infants in the rigid motion condition, the independent motion condition, or the baseline condition.

The analysis of proportion scores revealed a main effect of Order, $F(1,18) = 6.42$, $p < .025$, a main effect of Condition, $F(2,18) = 3.76$, $p < .05$, and an interaction of Condition × Test pair, $F(4,36) = 3.81$, $p < .025$. The order effect indicated that the preference for the separated rings was higher for those infants who were presented with separated rings first (.558) than for those presented with the connected rings first (.457). The main effect of condition indicated that the preference for the separated rings was influenced by habituation condition, as predicted: The proportion of looking at the separated rings was highest in the rigid motion condition (.578), lowest in the independent motion condition (.452), and intermediate in the baseline condition (.488). To investigate further the Condition × Test pair interaction, separate 3 (Habituation condition) × 2 (Order) analyses were conducted for each pair of test trials. Analysis of the first test pair revealed only a main effect of Order, $F(1,18) = 9.34$, $p < .01$: Proportion of looking at the separated rings was higher when those rings were presented first, regardless of habituation condition. The analysis of the second test pair revealed only a main effect of Condition, $F(2,18) = 3.72$, $p < .05$, as did the analysis of the third test pair, $F(2,18) = 5.72$, $p < .025$. The predicted effect of habituation condition on test preferences was obtained on the second and third pairs of test trials.[5]

For the 3 infants who had touched the center of the display during familiarization–all in the rigid motion condition–the proportion of looking at the novel (i.e., separated) rings averaged .573. For the other 5 infants in the rigid motion condition, the proportion averaged .580. If the infants who touched the center are removed from the sample, the preference for the novel display (i.e., the separated rings in the rigid motion condition and the connected rings in the independent motion condition) averaged .561, which significantly exceeds .5, $t(12) = 1.96$, $p < .05$, one-tailed.

Discussion

The findings of this experiment provide some support for the hypothesis that infants perceive the connectedness or separateness of surfaces they feel by detecting the surfaces' patterns of motion. Looking preferences between connected and separated rings were influenced by prior haptic exploration of rings that were rigidly or independently movable. Nevertheless, this finding was not strong (see footnote 5), and it was complicated by an interaction with test pair. Infants showed especially high levels of looking on the first visual test trial, regardless of which ring display was presented on that trial.

The high looking times on the first test trial suggest that looking patterns were influenced by the novel motion presented during the test. Neither the infants in the independent motion condition nor those in the rigid motion condition had tended, during the habituation period, to move the ring displays in a steady, horizontal translation. Rather, those in the former condition tended to move the rings in alternation, whereas those in the latter condition tended to move the rings in an irregular, vertical or rotary pattern. It seemed possible that infants would respond more clearly to the connections and boundaries in the visual displays if they were presented with test displays that underwent a less novel motion. Experiment 4 tested that possibility, by presenting infants with visual displays undergoing a jiggling motion such as that of Experiment 2.

[5] In the analyses of raw and log-transformed looking times, the predicted interaction of Condition × Test display was not significant: for raw times, $F(2,18) = 1.64$, $p < .25$; for logs, $F(2,18) = 3.13$, $p < .07$. The interaction of those factors with Test pair was significant: for raw times, $F(4,36) = 5.71$, $p < .002$; for logs, $F(4,36) = 3.58$, $p < .02$. In addition, these analyses revealed a main effect of Test pair, indicating that looking time declined over the test session, a main effect of Test display, indicating that infants looked longer at the separated rings, and interactions of Test display × Test pair, Test display × Order, and Test display × Test pair × Order. The latter interactions stem from the tendency to look longest on the first test trial.

Method

The method was identical to that of Experiment 3, except as follows.

Subjects. The 24 participants (13 boys, 11 girls) ranged in age from 3 months, 22 days to 4 months, 28 days (mean age, 4 months, 8 days). One additional infant was replaced due to fussiness.

Displays and apparatus. During the test trials, the ring display boards from Experiment 3 were suspended by 15-cm-long white strings from the top of the display. When agitated, a board underwent a unitary jiggling motion similar to the motion of the rigidly connected rings in Experiment 2. Since the boards were placed in a lower position against the background, each ring display was moved to a position 15 cm higher on its board so that it appeared at the same height and distance from the baby as in the previous experiments.

Procedure. As in Experiment 2, a white screen was lowered before each test trial by the first experimenter, and then the second experimenter positioned the test display and set it in motion by striking the display board with the hand. After the hand was withdrawn, the screen was lifted to reveal the jiggling ring display. Both the connected and the separated rings underwent the same pattern of motion. Test trial looking times for a subset of 12 infants were coded independently by two pairs of observers with moderately high reliability, $r = .90$.

Results

Habituation period. Characteristics of the habituation phase are presented in Table 4 and Fig. 6. All the infants met the criterion of habituation within 15 trials. Once again, there was some tendency to explore the independently movable rings longer than the rigidly movable rings. Three infants, all in the rigid motion condition, touched the center connecting the rings. Touching the center occured on a total of 5 of 123 trials (4%).

Test period. Test trial looking times are presented in Fig. 6. Infants who were habituated to the rigidly movable rings looked longer at the visibly separated rings, those who were habituated to the independently movable rings looked longer at the visibly connected rings, and those in the baseline condition looked about equally at the two test displays. A 3 (Habituation condition) × 2 (Order) × 3 (Test trial pair) ANOVA on proportion of looking at the separated rings revealed a significant main effect of Condition, $F(2,18) = 17.62$, $p < .0001$. The proportion of looking at the

TABLE 4
Characteristics of Habituation, Experiment 4

	Object motion		
	Rigid	Independent	$t(15)$
Holding, first 3 trials (s)	73.1	136.9	2.70*
Trials (No.)	8.1	9.5	<1
Total holding time (s)	157.0	193.4	<1

* $p < .02$, two-tailed.

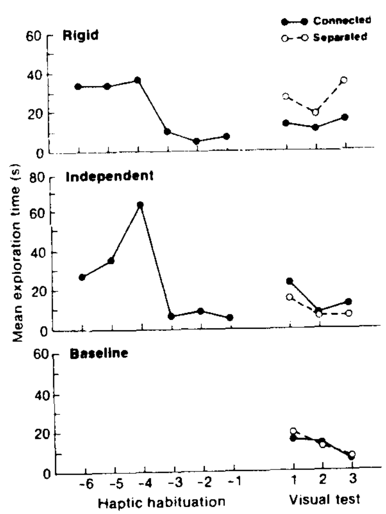

FIG. 6. Holding times and looking times in Experiment 4 by infants in the rigid motion condition, the independent motion condition, and the baseline condition.

separated rings averaged .580 in the rigid motion condition, .443 in the independent motion condition, and .517 in the baseline condition.

Two further ANOVAs comparing each experimental condition with the baseline condition revealed that both types of haptic familiarization led to preferences that differed from the baseline. Infants in the rigid motion condition showed a higher proportion of looking at the separated rings than did infants in the baseline condition, $F(1,12) = 10.54$, $p < .01$, and infants in the independent motion condition showed a lower proportion of looking at the separated rings than did those in the baseline condition, $F(1,12) = 8.56$, $p < .02$. No other effects were significant in these analyses.[6]

For the 3 infants who had touched the center of the rigid ring display, the proportion of looking time to the novel (i.e., visibly separated) ring display averaged .593; for the 5 remaining infants in the rigid motion condition, the proportion averaged .609. When the infants who touched the center are removed from the sample, the mean proportion of looking at the novel display is .578, which significantly exceeds .5, $t(12) = 4.16$, $p < .005$.

[6] The analyses of raw and log-transformed looking times both revealed the predicted interaction of Condition × Test display: for raw scores, $F(2,18) = 9.36$, $p < .002$; for logs, $F(2,18) = 16.16$, $p < .0001$. In addition, both analyses revealed main effects of Test pair and Test display: Looking times declined with successive trials and were higher, in general, for the separated rings display.

Discussion

Infants who manipulated the rigidly movable rings subsequently looked longer at rings that were separated, whereas those who had manipulated the independently movable rings subsequently looked longer at rings that were connected. Neither visual preference can be attributed to a baseline effect, to recognition of a particular motion pattern during the test, or to recognition of any feature of the displays that could have been felt by a single hand. Infants evidently perceived connected or separated objects by detecting the patterns of common or independent motion that they themselves produced.

The present experiment thus replicated the central finding of Experiment 3, that visual test preferences were influenced by prior haptic exploration. In contrast to Experiment 3, the test preferences were not complicated by order or trial effects. The use of a less novel motion in the visual test appeared to reduce the overall novelty of the first test trial and to allow the differential effects of the two bimanually produced motion patterns to emerge more clearly.

We conclude that young infants can perceive the unity and boundaries of objects by manipulating surfaces actively with two hands and by detecting their patterns of common or independent motion. When surfaces can only be moved rigidly together, infants perceive them to lie on a single object that extends through the region between their hands. When surfaces can be moved independently, infants perceive them to lie on distinct objects.

GENERAL DISCUSSION

The present experiments shed light on the early development of bimanual exploration, haptic discrimination, haptic-to-visual transfer, and object perception. We consider each of these topics in turn.

Bimanual Exploration

The infants in these experiments held and explored objects for extended periods of time. The average exploration time of 2½ min is 5 times greater than the average time that infants of this age have spent in visual exploration of similar objects, as measured by experiments conducted in the same laboratory as were the present studies (Steri & Pêcheux, 1986a, 1986b). These long holding times suggest that infants can and do manipulate objects with two hands, out of the field of view.

Do infants truly explore objects bimanually, or do they hold them passively? To address this question, it would be interesting to compare the exploration times in the present experiments with the exploration times of infants presented with a single object in one hand. A preliminary comparison of this type is possible, for experiments on unimanual haptic habituation have been conducted in the present laboratory with infants of this age (Streri & Pêcheux, 1986a, 1986b). One of the objects presented for unimanual habituation was a square with a round, central hole that was identical in substance and texture, and very similar in size and weight, to the rings used in the present studies. This object was always presented to the right hand: the hand that was less likely to drop an object in the present studies (see Experiment 1). The apparatus and the procedure were the same as in the present studies, except for the criterion of habituation. Accordingly, the habituation data from Streri & Pêcheux (1986a, 1986b) were reanalyzed for the infants presented with the square-with-hole, following the criterion of the present experiments and discarding any trials that were given after the present criterion was met. Infants who did not meet the present criterion were removed from the sample, leaving a group of 6 infants.

Table 5 presents the habituation data for these infants, compared to the data for the 24 infants in Experiment 1. It can be seen that infants in the bimanual experiment explored almost twice as long as those in the unimanual experiment. This was true even for infants who explored the rigidly connected rings (see Table 1), whose hand movements were quite constrained. If infants had not engaged in bimanual exploration, then holding times should have been lower in the bimanual experiment, even in the independent motion condition, since infants had twice as many chances to end each bimanual trial (by dropping either ring). The finding that those times were longer suggests that infants do engage in systematic bimanual exploration when their hands grasp objects outside the visual field.

In several of the present experiments, infants explored the independently movable rings longer than the rigidly movable rings. This trend was not significant in all the experiments or on all measures, but it appeared with some consistency. What could have produced it? One possibility is that infants have greater difficulty holding two rings that are rigidly connected, since each movement of one hand tends to pull the object away from the other hand. Two considerations weigh against this possibility. First, exploration times were higher in the rigid motion condition than in the unimanual experiments: the opposite of what one would expect if actively moving one ring led to passive release of the other. Second, the number of trials to the criterion of habituation did not differ systematically in the rigid and independent motion conditions. If rigid motion trials were ended prematurely because of accidental release of one ring, then more trials to habituation should have been required.

TABLE 5
Unimanual and Bimanual Holding Times during Haptic Habituation

	Condition		
	Unimanual[a]	Bimanual[b]	$t(15)$
Holding, first 3 trials (s)	50.8	95.0	2.27*
Trials (No.)	7.7	7.3	<1
Total holding time (s)	104.3	156.8	2.06*

[a] From Streri & Pêcheux (1986a) and Streri & Pêcheux (1986b).
[b] From Experiment 1.
* $p < .05$, two-tailed.

A second possibility is that infants perceived the independently movable rings as two distinct objects and the rigidly movable rings as one object, and that infants tend to explore two objects presented simultaneously longer than one object presented alone. This conjecture is supported by the finding that infants explored the separated rings longer than the connected rings on visual as well as haptic trials (see footnotes 5 and 6). We return to the question of object perception below.

Although the present experiments provide evidence for an early capacity for bimanual exploration, they suggest at least two limits to the young infant's haptic exploration. First, infants did not bring the objects they held into view. During haptic familiarization, only a soft cloth prevented infants from seeing the objects in their hands: a determined subject could have circumvented this obstacle by bringing the objects around the side of the cloth or even up through the opening at his neck. Despite the lengthy periods of haptic exploration, few infants attempted this, and none was successful. Haptic exploration did not appear to be coordinated with vision in this situation. Second, infants did not tend to explore by moving their hands over the objects they held. This limit is reflected in the low incidence of attempts to touch the bar or elastic that connected the two rings in a display. During the haptic trials, the bar or elastic could readily be touched by changing the grip on a ring or sliding the fingers along the display, but most infants never did this. Instead, infants grasped the rings firmly and displaced them by moving their arms.

Experiments from other laboratories confirm that young infants do not attempt to look at what they feel or to explore surfaces haptically beyond the regions within their immediate grasp (Hatwell, 1986). This limit has been taken to indicate that young infants are captive to their immediate sensory impressions: They are aware of what they are feeling, but they have no notion that the surfaces they feel could be seen or could extend into regions beyond their grasp. The present experiments cast strong doubt on this interpretation. Although the infants in our studies did not attempt to look at the rings they felt, they were able to recognize visually what they had felt in a subsequent transfer test. Furthermore, although most infants did not attempt to feel the connection or separation between the rings they held, they were evidently able to perceive whether or not the rings were connected. We now turn to these findings.

Haptic Discrimination and Intermodal Transfer

The findings of Experiments 1 and 2 provide evidence that infants can discriminate between objects that they move rigidly and objects that they move independently, and that this discrimination transfers to vision. In one sense, these findings complement previous research. Infants this age, and even younger infants, have been shown to discriminate among objects presented only to one hand if the objects differ in form or substance (Streri, in press; Streri and Pêcheux, 1986a; Rochat, 1985). In some experiments (e.g., Streri, in press), although not others (Streri and Pêcheux, 1986b), this discrimination has been found to transfer to vision. Haptic discrimination and haptic-to-visual transfer have also been observed at young ages when infants explore forms or substances in the mouth (Gibson & Walker, 1984; Meltzoff & Borton, 1979). Thus, the present studies join a growing body of research that suggests an early development of sensitivity to haptic information and to haptic–visual relationships.

The present findings extend the above research by demonstrating that infants are sensitive to information they produce themselves by coordinated activities of the two hands. In these experiments, the infants explored surfaces that differed only with respect to their potential relative motions. The experiments provide evidence that young infants actively produce such motions with two hands, that they discriminate one motion pattern from another, and that their perception of the relative motions of surfaces is abstract enough to permit them to recognize the same surfaces visually.

Haptic Perception of Objects

The findings of Experiments 3 and 4 provide evidence that infants who explored the rigidly movable rings perceived the rings as parts of a single connected object, whereas those who explored the independently movable rings perceived the rings as distinct, separated objects. These experiments are the first, we believe, to demonstrate an early capacity for object perception in the haptic mode. They provide evidence that the perceptual world of an infant, exploring with her hands, is not limited to the patches of surfaces she feels. Like the adult (Gibson, 1962), the infant

apprehends an extended layout of objects from her scattered contacts with surfaces, a layout which continues beyond the particular regions she feels.

This finding casts doubt on a number of claims about perceptual and cognitive development, including the claims of traditional empiricists (e.g., Helmholtz, 1885) and of Piaget (1954). According to these theories, perception of a world that extends beyond immediate sensory experience is the product of a long process of construction, undertaken by the infant or toddler as she explores. Particularly important to this process are the infant's simultaneous investigations of the world by looking and touching. Beginning at the end of the fifth month and extending into the second year, infants systematically attempt to manipulate what they see and to see what they manipulate. These investigations, it is said, lead infants to construct an objective and enduring world.

Experiments in the visual mode already provide evidence against this view. Before the onset of visual–haptic coordination, infants perceive the visual world to extend beyond the surfaces reflecting light to the eye. They perceive objects to extend behind other objects that partly occlude them (e.g., Kellman & Spelke, 1983) and to continue to exist when they move fully out of view (Baillargeon, Spelke, & Wasserman, 1985; Spelke & Kestenbaum, 1986). The present experiments, which were also conducted with prereaching infants, provide evidence for an analogous capacity in the haptic mode.

The present experiments provide evidence that infants perceive objects haptically by analyzing the motions of surfaces. Under conditions in which the connectedness or separateness of two surfaces is not felt directly, the surfaces are perceived to lie on a single object if they can only be moved rigidly together and they are perceived to lie on separate objects if they can be moved independently. These motion patterns also provide information for object unity and boundaries in the visual mode. When two visible surfaces are arranged in depth such that no connection or separation between them can be seen, for example, infants perceive the surfaces to lie on a single connected object if they move rigidly together, and they perceive the surfaces to lie on distinct objects if they move independently (Hofsten & Spelke, 1985). Infants thus appear to perceive objects under the same conditions whether they encounter them by looking or by touching.

This finding raises the possibility that object perception depends on a single, relatively central mechanism, rather than on a collection of mechanisms that are modality specific. This mechanism would begin to function only after modality-specific processes had yielded a representation of the surface layout and of changes in the layout. It would group surfaces in this representation onto objects by analyzing their perceived arrangements and motions, without regard to the sensory sources or correlates of these properties.

Experiments in the visual mode lend plausibility to this view. First, infants' perception of visible objects has been found to depend on the perceived motions of surfaces, not on any particular optical variable (Kellman *et al.*, 1986; Kellman, Gleitman, & Spelke, in press). This finding suggests that the input to the mechanism for apprehending objects is itself the product of considerable visual processing. Second, infants appear to apprehend objects in ways that resemble mature patterns of thought more than they resemble what should be kindred processes of visual perception. For example, infants do not organize the visual world into objects by detecting gestalt relationships such as contour alignment (Kellman & Spelke, 1983; Schmidt & Spelke, 1984; Schmidt et al., 1986) or by weighting a set of separate and normally redundant cues to object unity (Spelke, Hofsten, & Kestenbaum, 1986), as do mature perceivers of form and depth. Rather, infants appear to analyze surface arrangements and motions much as adults do when reasoning about the physical world (see Spelke, in press).

All these findings suggest that objects are not "perceived," in some strict sense of that term, but are known by virtue of a mechanism of thought, an "object concept." It is possible, however, that objects are apprehended by modality-specific perceptual processes, themselves inferential in character, that mirror each other and mimic processes of thought (e.g., Bruner, 1957; Fodor, 1983; Helmholtz, 1885; Rock, 1984). In either case, the present findings provide evidence that object perception develops early in infancy, without benefit of extensive haptic experience. Before the onset of visually-guided reaching, infants perceive a layout of continuous and bounded objects from their fragmentary encounters with surfaces, both in the visual and in the haptic mode.

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