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Infants' haptic perception of object unity in rotating displays

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Four-month-old infants were allowed to manipulate, without vision, two rings attached to a bar that permitted each ring to undergo rotary motion against a fixed surface. In different conditions, the relative motions of the rings were rigid, independent, or opposite, and they circled either the same fixed point outside the zone of manipulation or spatially separated points. Infants' perception of the ring assemblies were affected by the nature of the rotary motion in two ways. First, infants perceived a unitary object when the felt ends of the object underwent a common, rigid rotary motion; perception of object unity was stronger in this condition than when the ends underwent either independent or opposite rotary motions. Second, infants perceived two distinct objects when the felt ends of the objects underwent independent rotary motions that centred on distinct fixed points. Perception of the distinctness of the objects was less clear when the ends underwent opposite or independent rotary motions that centred on a common fixed point. These findings provide the first evidence that infants are sensitive to rotary motion patterns and can extrapolate a global pattern of rigid motion from the distinct, local velocities that they produce and experience at their two hands.

Our environment is composed of objects that enter into a rich variety of spatial relationships including contact, connection, containment, and occlusion. Numerous experiments have investigated how infants understand these relationships, by presenting infants with systematically varying object motions and configurations (see Kellman & Arterberry, 1998, for review). In both the visual and the haptic modes, infants have been found to perceive objects by

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detecting patterns of translatory motion. For example, 4-month-old infants perceive the two ends of a visually presented, centre-occluded object as one connected unit when the ends undergo a common translation (Eizenman & Berthenthal, 1998; Johnson & Aslin, 1996; Johnson & Nañez, 1995; Jusczyk, Johnson, Spelke, & Kennedy, 1999; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986; Slater, Morison, Somers, Mattock, Brown, & Taylor, 1990), and they perceive two adjacent objects as separate units when the ends undergo relative translations (Hofsten & Spelke, 1985; Spelke, Hofsten, & Kestenbaum, 1989). In the haptic mode, similarly, infants who explore the two ends of a haptic assembly with one end in each hand perceive the ends as one connected unit when they undergo a common rigid motion (Streri & Spelke, 1988, 1989) and as two distinct units when they undergo different translatory motions (Streri, Spelke, & Rameix, 1993). In neither mode is perception of object unity affected by the similarity of the moving parts in shape or texture (Kellman & Spelke, 1983; Streri & Spelke, 1989). These observations are consistent with the hypothesis that translatory motion specifies object unity for infants.

In contrast, studies of object perception in the visual mode provide no evidence that infants perceive object unity when objects undergo a different rigid motion: rotation. Infants' perception of objects in rotary motion has been studied in two laboratories (Eizenman & Berthenthal, 1998; Kellman, 1993), with similar findings. In Eizenman and Bertenthal's studies, 4- and 6-month-old infants were habituated to a centre-occluded rod that underwent oscillating translation, continuous rotation, or oscillating rotation, and then these infants, and other infants in baseline conditions involving no habituation to rod displays, were presented with fully visible continuous and broken rods, in alternation, that underwent the same patterns of motion. The infants who were habituated to the centre-occluded rod in translatory motion looked reliably longer at the broken translating rod relative to baseline. This replicates Kellman and Spelke's (1983) findings and provides further evidence that infants perceive this partial occlusion display as a connected object. In contrast, only the 6-month-old infants who were habituated to the centre-occluded rod in rotary motion showed a reliable preference for the broken test display (see also Kellman, 1993). Although oscillating translation specified a unitary object to 4-month-old infants, continuous rotation specified a unitary object only at 6 months, and oscillating rotation failed to specify a unitary object even at the older age. These findings provide evidence for a developmental change, from 4 to 6 months, in infants' ability to perceive object unity in continuously rotating displays. They suggest, moreover, that 6-month-old infants' sensitivity to object unity in rotating displays is fragile, because no such sensitivity is observed when infants view an oscillating rotation. In contrast, infants of 2 and 4 months perceive the object unity that undergoes an oscillating translatory motion, regardless of whether that motion causes accretion and deletion of surface texture (e.g., Johnson & Aslin, 1995; Kellman et al., 1986).

Why does rotary motion fail to specify object unity for 4-month-old infants? One possibility is that infants fail to perceive a unitary rotating object in the visual mode because the visual information for rotary motion is complex in relation to the primate visual system (Eizenman & Bertenthal, 1998). In a lateral translatory motion, all points on an object undergo displacements at identical velocities; in a lateral rotary motion, in contrast, each point on an object moves at a different velocity, and the ends of the object move in opposite directions. A wealth of evidence, from neurophysiological studies of nonhuman primates to psychophysical studies of human adults, suggests that the latter motions are more difficult to process (see Eizenman & Bertenthal, 1998, for review).

The present experiments investigate infants' perception of rotating objects under conditions that are designed to eliminate these difficulties. First, the experiments focus on object perception in the haptic mode, which may be better adapted to exploring the properties of rotating objects. When a perceiver holds and actively moves the ends of a rotating object, the rigidity of its motion may be more apparent, because every force exerted on one end of the object will be felt at the other end. Second, the experiments focus on infants' perception of the unity of rotating objects whose ends move in the same rather than opposite directions, by having the ends rotate around an eccentric pivot point. If infants can perceive object unity from rotary motion, we reasoned, the present displays may better elicit that capacity.

The experiments used Streri and Spelke's method (1988, 1989; Streri et al., 1993). Thus, infants were presented with two rigid rings, one in each hand, under conditions that masked their view of the rings, of the apparatus to which the rings were connected by a bar, and of their own bodies. Infants were allowed to manipulate the rings at will on a series of habituation trials; each trial ended when an infant dropped a ring, and the trial series ended when their manipulation times declined to a habituation criterion. Then, infants were presented with visual displays in which the rings were either visibly connected or visibly separate, on alternating trials. If infants had perceived the rings that they manipulated as a single connected object, they were expected to look longer at the visibly separated rings; if they had perceived two unconnected objects, they were expected to show the opposite preference.

In the present studies, the bar attached to each ring was connected to a stationary board by a screw, such that the ring could be rotated about that fixed point but could not be displaced in other ways (see Figure 1). In different conditions, we investigated infants' perception of object unity in relation to two properties of these assemblies. First, we varied whether the two rings were connected to the same pivot point or to spatially separated pivot points. Second, we varied whether the two rings underwent a single rigid, rotary motion, opposite rotary motions (like scissors), or independent rotary motions. Over three experiments, therefore, we asked whether infants perceive object unity in the haptic mode on the basis of patterns of rotary motion, and whether their perception is affected by specific spatial and temporal properties of the motion patterns. Because adults' studies are essential to understand infant's perception, adults' perception of the displays was also assessed (see Appendix).

EXPERIMENT 1

In the present experiment, the infants were familiarized haptically with objects that underwent either unconnected and independent or connected and rigid rotary motions (Figures 1a and 1b). The infants produced these motions actively, by rotating the two rings or by exerting opposing forces on the rings without moving them. In the first condition, the rings rotated around distinct fixed points, and their rotating motions were independent ("unconnected independent motion assembly"). In the second condition, the rings rotated around a common fixed point and could only be moved together rigidly ("connected rigid motion assembly"). For purposes of comparison, the infants in a third baseline condition received no haptic

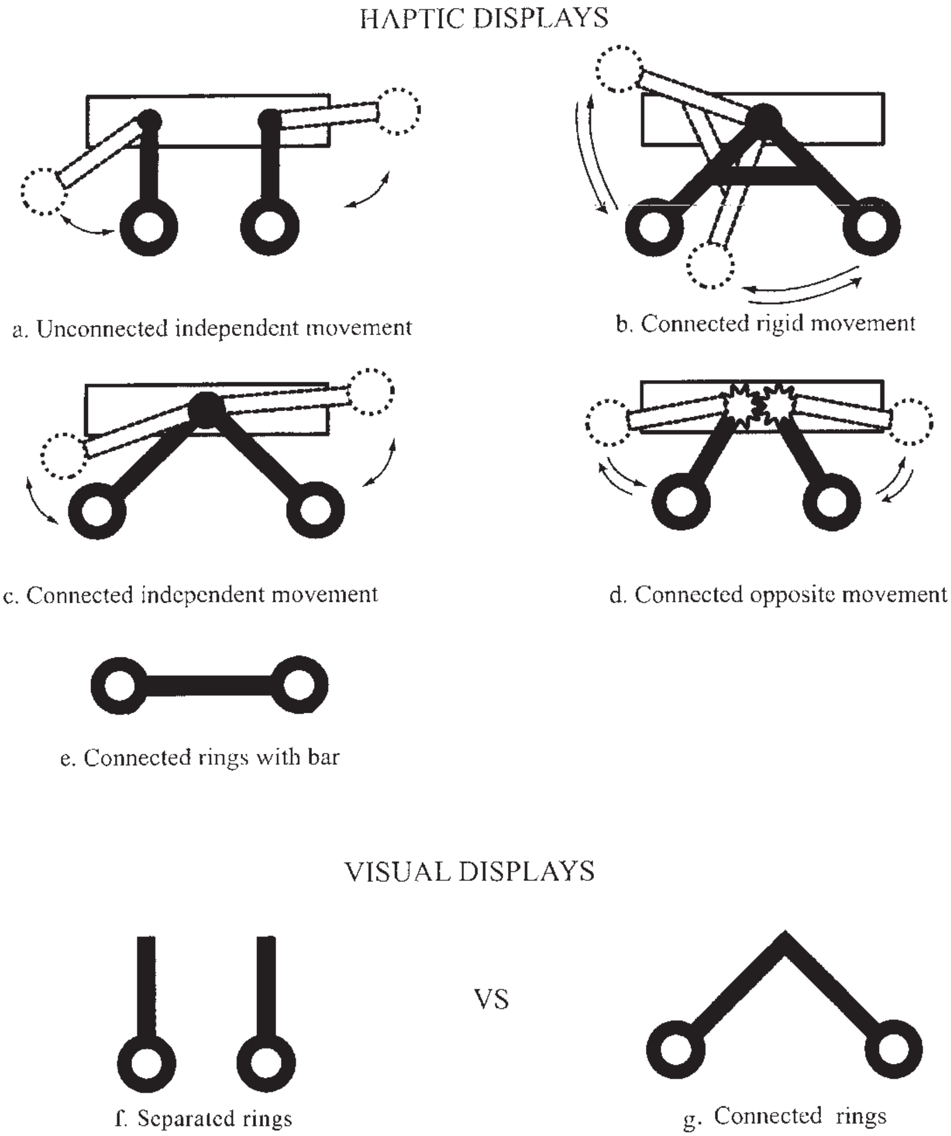

Figure 1. Displays presented to the infants in Experiments 1, 2, and 3 (a–d and f–g) and adults (a–e) (see Appendix).

familiarization. If the infants perceived the unconnected independent motion assembly as two separated objects, then they were expected to look longer at the connected visual display. If the infants perceived the connected rigid motion assembly as one connected object, then they were expected to look longer at the separated visual display. Looking preferences in the two experimental conditions therefore should differ from each other and from preferences in the baseline condition.

Method

Subjects

Participants were 48 infants ranging in age from 4 months, 17 days to 4 months, 29 days (M = 4 months, 15 days). The 20 boys and 28 girls were born of full-term pregnancies, were in good health, and resided in Paris. An additional 11 subjects were eliminated because of procedural errors (2), fussiness (4), or failure to produce the rotating motion of the object (5; see below).

Displays and apparatus

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

Figure 1 presents the haptic object assemblies and the visual displays. The haptic assemblies (Figures 1a and 1b) consisted of two wooden rings, 45 mm in diameter and 8 mm thick, each connected to a wooden bar that was in turn connected by a screw to one or two axes on a 300 mm × 145 mm white wooden support. The axes were 110 mm metal bars that separated the ring assembly from the support. In the unconnected independent motion assembly, each ring was connected to a distinct axis, and the two connections (as each ring centre) were separated by 105 mm. The rings therefore could be rotated independently of one another. In the connected rigid motion assembly, the two rings were connected rigidly to one another by a single 60 mm axis, and the gap between each ring centre was 150 mm (see Figure 1b). The rings, therefore, could only be conjointly moved in a rotating synchronous manner and underwent no relative motion. Infants directly touched only the rings at the ends of these assemblies, thereby producing the independent or rigid rotary motion. The visual displays consisted of two wooden bars with rings of the same dimension. In one-object display, the two bar-rings formed a single, connected object. In the two-object display, the two bar-rings were separated by a gap of 100 mm and thus formed two distinct objects. Each visual display was mounted 100 mm in front of a white 400 × 200 mm panel by concealed metal rods. The panel was suspended from the front of the enclosure by strings that were hidden behind the curtain. During the visual test trials, the panel containing a visual display was agitated, such that the display underwent a rigid, jiggling motion. At its distance of 500 mm from the infant, the one-object display spanned an area of 17°44′, and the two-object display spanned 15°38′.

Design

Equal numbers of infants participated in the three conditions: unconnected independent motion, rigid connected motion, and baseline. Within each condition, the order of visual test trials (one-object first or two-object first) were counterbalanced.

Procedure

Experiment 1 followed closely Streri and Spelke (1988, 1989) and Streri et al.'s (1993) method. Haptic habituation trials began as soon as the infant was seated, and the cloth was positioned over their body. The first experimenter, seated to the right of the infant, placed the infant's hands into the rings of the assembly. At the start of each habituation trial, the infant was given an object assembly and was allowed to manipulate it at will. As in previous research, infants tended to explore an assembly by grasping the rings and displacing them, but not by moving their fingers over the assembly so as to contact other parts of the assembly. When an infant released either one or both rings after holding both rings for at least 1s, the second experimenter signalled the end of the trial to the first experimenter, who removed the other ring if necessary and then placed the rings in the infant's two hands again, beginning the second trial. A trial was also ended after 90 s of continuous holding. Trials were continued until 15 trials were presented or a criterion of habituation had been met, whichever came first. The criterion was a 50% decline in holding time on three successive trials, relative to holding time on the first three consecutive trials for which the total holding time equalled or exceeded 30 s. All infants therefore received between 6 and 15 trials.

In order to ensure that every infant in the final sample had adequate exposure to the critical motion of the haptic assembly, infants were retained in the sample only if (1) they produced the relative motion at least once on at least half the habituation trials, and (2) they manipulated the assembly for at least 30 s during three consecutive habituation trials. Decisions to reject an infant were made by two observers who had not served as experimenters and had not been present during the experiment itself. These observers calculated holding times and assessed manipulation patterns from the video recording.

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

Test trial looking times were coded from the video recording by the same two observers. Neither the visual displays nor the curtain that covered a display between trials appeared on the video recording; visual trial onset was indicated by the infant's behaviour, who looked at the display after the curtain was parted. The observers therefore coded an infant's looking time in ignorance of the particular display that the infant viewed on any given trial and of the time when the experimenters had decided to end the trial. Interobserver reliability was assessed by calculating the total test session looking time recorded for each infant by the two video observers and by computing the correlation coefficient between these two recordings. Reliability was high, $r(47) = .92$.

Analyses

Preliminary analyses on the holding times in seconds in haptic habituation conditions showed that order and gender factors had no significant effect and did not interact with other factors. Consequently, results were collapsed across order and gender conditions. Manual exploration times and habituation patterns were compared for the two different ring assemblies (connected rigid vs. unconnected independent) by *t* tests. Preferences between the test displays were analysed in each condition by 3 (trial pair) by 2 (display) repeated measures analyses of variance (ANOVAs) and by sign tests. Then, looking times during the test trials were compared by a 3 (condition: connected rigid vs. unconnected independent vs. baseline) by 3 (trial) by 2 (display: connected vs. separated) ANOVA and preplanned comparisons, with the two last factors within subjects, to determine whether looking patterns were different for the infants in different habituation conditions.

Results

Characteristics of the haptic habituation phase are presented in Table 1 (a and b). Exploration times were similar to those obtained in past experiments (Streri & Spelke, 1988, 1989; Streri et al., 1993). Comparisons across the different conditions revealed no differences in mean holding times on the first three trials, total holding times, or number of habituation trials for the infants who manipulated the two ring assemblies, all *t*s < 1. Informal observations of the videotapes suggested that, after several attempts to push or pull the bar-rings, infants produced the relative independent motion by rotating the bar-rings with their right or their left hand, but rarely with both hands simultaneously. Infants also rarely displaced the independent motion assemblies far enough to arrive at the endpoints of the motion. In the connected rigid motion condition, infants produced synchronous motion by displacing the two bar-rings simultaneously on the left or right side. This motion was constrained by the assembly.

Figures 2a, 2b, and 2e present the mean looking times on the six visual test trials. Infants habituated to the connected rigid motion looked more at the separated test display ($M = 29.5$; $SD = 10$) than the connected test display ($M = 22$; $SD = 12$). This preference was shown by 13 of the 16 infants ($p < .05$, sign test) and yielded a significant effect of display, $F(1, 15) = 10.35$, $p < .01$. An effect of display was also observed in infants habituated to the independent motion condition, $F(1, 15) = 8$, $p < .05$, who looked more at the connected test display ($M = 39.6$; $SD = 23.3$) than the separated test display ($M = 25.5$; $SD = 10.8$). This preference was shown by 13 of the 16 infants ($p < .05$, sign test). In the baseline condition, the effect of display was not significant, $F(1, 15) = 0.17$, $p > .20$: Infants looked approximately equally at the separated test display ($M = 34.9$; $SD = 26.6$) and the connected test display ($M = 37.3$; $SD = 23$). Nine infants looked longer at the connected display, and seven looked longer at the separated display.

The general ANOVA revealed a significant effect of trial, $F(2, 90) = 4.44$, $p < .05$, and a significant interaction of condition by display, $F(2, 45) = 5.46$, $p < .01$. No other effects were

TABLE 1
Characteristics of haptic habituation

	Mean holding time[a]				*Mean number of trials*		*Total holding time*	
	First 3 trials		*Last 3 trials*					
Conditions	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
a. Unconnected independent movement	55.37	44.19	6.79	3.52	9.44	2.53	141.50	67.99
b. Connected rigid movement	47.84	33.52	6.15	2.27	9	3.58	127.72	104.75
c. Connected independent movement	56.19	41.32	7.78	5.58	8	2.50	123.94	89.63
d. Connected opposite movement	57.31	54.23	6.16	3.89	9.44	3.42	126.94	62.05

[a]In s.

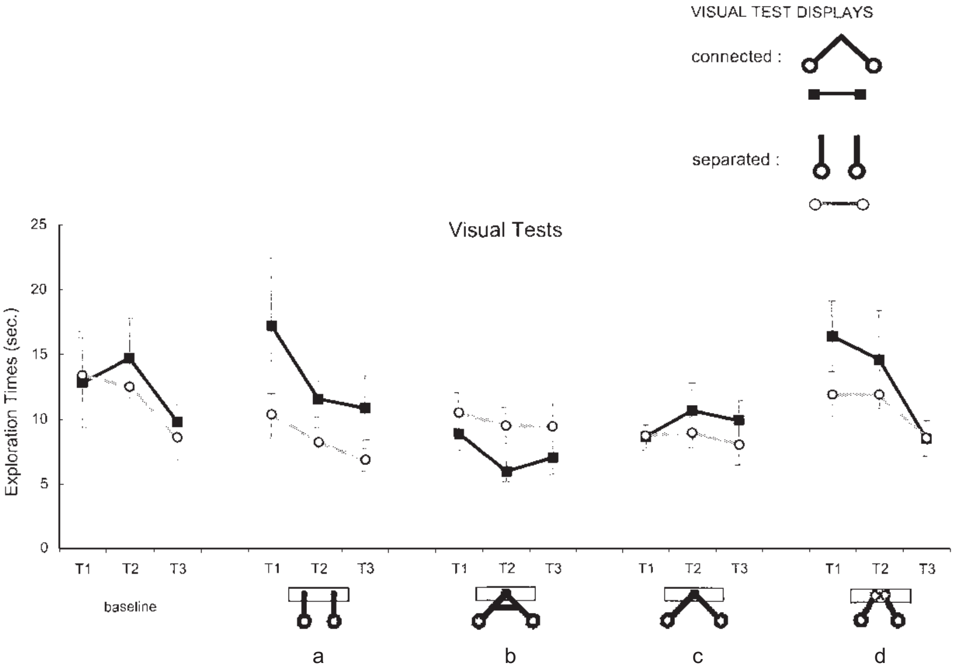

Figure 2. Mean looking times on the last six habituation trials and on the six test trials for the infants in Experiments 1 (a, b, and baseline), 2 (c), and 3 (d).

significant. The first effect indicates that looking time declined over the course of successive pairs of trials. Most important, the interaction indicates that preferences between the test displays differed across the different haptic habituation conditions. Preplanned analyses focused on test preferences of infants revealed a significantly opposite preference only between unconnected independent motion and connected rigid motion conditions, $F(1, 45) = 10.91$, $p < .01$.

Discussion

Infants who were habituated to the rings that underwent unconnected, independent motion subsequently looked longer at a visual display of connected rings than at a visual display of separated rings, whereas infants habituated to the rings that underwent connected, rigid motion subsequently showed the reverse preference. Because the two visual test displays differed only with respect to the connectedness or separateness of the rings, and because no baseline preference between the visual displays was found, these looking preferences provide evidence that infants perceived the connectedness or separateness of the surfaces that they explored manually by detecting the surfaces' patterns of rotary motion. Experiment 1 nevertheless does not reveal whether infants differentiated between the two patterns of rotary motion by analysing information about the motion relationships or the spatial relationships in these displays. It is possible that infants perceived two unconnected objects in the unconnected independent motion assembly because the objects underwent independent motions:

Motions of the object in the left hand engendered no corresponding motion in the right hand. Alternatively, it is possible that infants perceived two unconnected objects in this display because they perceived the rigid motions of the objects in each hand to centre on different (unfelt) pivot points: The point where the object on the left was attached to the display board was spatially separated from the point of attachment of the object on the right. These possibilities are not mutually exclusive: Infants may be sensitive both to the kinematic and to the spatial properties of objects in rotary motion. These possibilities were investigated in Experiment 2.

EXPERIMENT 2

The infants in Experiment 2 were presented with an assembly of two rings that rotated freely about one common fixed point (connected independent motion; Figure 1c). In this assembly, as in the unconnected independent motion assembly of Experiment 1, each ring could be moved independently of the other ring. The only difference between the independent motion assemblies concerned the locations of the fixed points around which the rotations occurred: The two rings rotated around two fixed points in Experiment 1 and around one common fixed point in Experiment 2. These centres of rotation could not be felt directly by the infants, but in principle they could be inferred from the paths of motion of the rings in the infants' hands. We therefore investigated whether they influenced infants' perception of object boundaries.

Infants' looking preferences in Experiment 2 were compared to those of each of the haptic habituation conditions in Experiment 1. If infants' perception of object unity in rotating displays depends only on the presence of rigid versus independent motion, then the infants in the connected independent motion condition of Experiment 2 should have shown the same visual test preferences as those in the unconnected independent motion condition of Experiment 1 and different test preferences from those in the connected rigid motion condition of that experiment. If infants' perception of object unity in rotating displays depends only on the presence of separated versus coincident centres of rotation, in contrast, then the infants in the connected independent motion condition should have shown the same visual test preferences as those in the connected rigid motion condition of Experiment 1 and different test preferences from those in the unconnected independent motion condition. Finally, if infants perceive object unity in rotating haptic assemblies by detecting both the motion patterns and the spatial arrangements of the centres of rotation, then looking preferences in the connected independent condition of Experiment 2 should have differed from those in each of the haptic habituation conditions of Experiment 1.

Method

The design, procedure, and analyses were the same as those in Experiment 1. The haptic assembly was the same as that in the connected rigid condition of Experiment 1, except that the two rings and bars rotated independently around their common axis (see Figure 1c). Participants were 16 infants (10 boys, 6 girls) aged 4 months, 2 days to 5 months, 0 days (M = 4 months, 15 days). An additional 4 subjects were eliminated because of fussiness (2) or experimenter error (2). Interobserver reliability was again very high (r = .98).

Results

Table 1(c) presents the characteristics of the haptic habituation period. Haptic exploration times did not differ significantly either from those of infants in the unconnected independent motion condition or from those of infants in the connected rigid motion condition, both *t*s < 1.

Figure 2c presents the mean looking times on the visual test trials. Infants habituated to the connected independent motion tended to look longer at the connected test display ($M = 29.5$; $SD = 13.7$) than at the separated test display ($M = 25.62$; $SD = 12.3$). However, this tendency was not observed on the first pair of trials and appeared to be weak. In particular, there was no effect of display on infants' looking preferences, $F(1, 15) = 2$, $p > .10$. A total of 12 of the 16 infants looked longer at the connected test display ($p > .05$, sign test).

A comparison between the two habituation conditions of Experiment 1 and the connected independent condition of Experiment 2 was performed. A 3 (condition: connected independent vs. connected rigid vs. independent unconnected) × 3 (trial) × 2 (display) ANOVA revealed a significant interaction of condition by display, $F(2, 45) = 9.64$, $p < .01$, and no other effects. A first preplanned comparison revealed that infants in the connected rigid motion condition of Experiment 1 looked reliably longer at the separated test display than those in the connected independent motion condition of Experiment 2, $F(1, 45) = 19.28$, $p < .001$. A second preplanned comparison of the connected versus unconnected independent motion conditions revealed a significant interaction condition by display, $F(1, 45) = 4.62$, $p < .05$: The looking preference for the connected display was greater in the unconnected independent motion than in the connected independent motion condition.

Discussion

Infants who manipulated two rings that underwent independent rotary motions from a common, fixed pivot point appeared to have no determinate perception of the connectedness or separateness of the rings: After habituating to this assembly, infants' preferences between the connected and separated visual test displays did not differ reliably. Infants' perception of the connectedness of the rings in this assembly was reliably lower than that of the infants in Experiment 1 who manipulated two rings that underwent rigid rotary motion from a common fixed point. This finding provides evidence that infants' haptic perception of object unity is influenced by the relationship between the rotary motions of its parts: independent versus rigid rotary motion. Infants' perception of the separateness of the rings in this assembly was also lower than that of the infants in Experiment 1 who manipulated two rings that underwent the same independent motions from two distinct pivot points. This difference suggests that infants are sensitive to the locations of the fixed points and of rotary motions. This finding might be explained in two different ways. First, infants may have perceived a connected object in the rigid motion assembly of Experiment 1, and not in the independent motion assembly of Experiment 2, because they perceived that the two ends of that object moved *rigidly* with respect to one another: The rods underwent the same rotation about the same fixed point. In contrast, the ends of the assembly in Experiment 2 moved nonrigidly with respect to one another. Alternatively, infants may have perceived a connected object in the rigid motion assembly of Experiment 1, because they perceived that the two ends of that object moved *contingently*: Any force exerted on one ring caused a corresponding motion of the other ring. In contrast, the motions of the ends of the assembly in Experiment 2 were not contingently related: Each ring could be moved without influencing the other. The last experiment investigated whether infants' haptic perception of object unity depends on the detection of rigid rotary motions, of contingent rotary motions, or of both motion relationships.

EXPERIMENT 3

Infants were presented with a ring assembly that could be displaced at will in a rotary motion, but in which both rings moved synchronously in opposite directions. The assembly therefore constrained the infants' movements of exploration as tightly as did the rigid motion assembly of Experiment 2, but the constraints specified two opposite rotary motions rather than one rigid rotary motion. Infants' perception of this assembly was tested by comparing the looking preferences of the infants in Experiment 3 both to those of the rigid motion condition of Experiment 1 and to those of the connected independent motion condition of Experiment 2. If infants perceive a unitary object by detecting any contingent patterns of haptically produced motion, then the infants in Experiment 3 should have perceived a connected object and looked longer at the separated test display. If infants perceive a unitary object only by detecting a pattern of common rigid motion, then the infants in Experiment 3 should have perceived two separated objects and looked longer at the connected test display. Finally, if infants' perception of object unity is influenced both by the rigidity and by the contingency of object motion, then the infants in Experiment 3 should have no determinate perception of object unity. Their perception of the connected opposite motion assembly should have been ambiguous, yielding less preference for the separated display than that of the infants in the rigid motion condition and less preference for the connected display than that of infants in the connected independent motion condition.

Method

The design, procedure, and analyses were the same as those in Experiments 1 and 2, and the haptic assembly consisted of the same connected ring and bar arrangement as in Experiment 2, except that two small notched wheels constrained the ring displacements such that when one ring was moved, the other ring moved in the opposite direction. Any force applied to one ring therefore produced an opposite force at the other ring (see Figure 1d). Participants were 16 infants (5 boys, 11 girls) aged 4 months, 2 days to 4 months, 29 days (M = 4 months, 19 days). One additional crying infant was eliminated. Interobserver reliability was again very high ($r = .97$).

Results

Table 1d presents the characteristics of the haptic habituation period. Haptic exploration times did not differ significantly from those of either the connected rigid motion condition of Experiment 1 or the connected independent motion condition of Experiment 2, $ts < 1$.

Figure 2d presents the mean looking times on the visual test trials. Infants tended to look longer at the connected test display ($M = 39.6$; $SD = 27.2$) than at the separated test display ($M = 31.9$; $SD = 14.8$), but they showed high variability in their looking times. A total of 7 infants looked longer at the connected test display, 7 infants looked longer at the separated test display, and 2 infants looked equally at the two test displays. The analyses revealed a significant effect of trial, $F(2, 30) = 5.32$, $p < .01$, but no significant effect of display, $F(1, 15) = 2$, $p > .10$. The first effect indicates that looking time declined over the course of successive pairs of trials.

A 3 (condition) × 3 (trial) × 2 (display) ANOVA, comparing looking preferences in Experiment 3 to those of the connected rigid condition of Experiment 1 and the connected independent motion condition of Experiment 2, revealed a significant effect of trial, $F(2, 90) = 3.82$, $p < .05$, a significant interaction of condition by trial, $F(4, 90) = 2.94$, $p < .05$, and a significant interaction of condition by display, $F(2, 45) = 4.74$, $p < .01$. The first two effects indicate that looking times declined over trials and that the decline was greater in the opposite condition than in the other conditions. Most important, the last effect indicates that infants in the three conditions showed different preferences between the test displays, and so these differences were analysed further.

The first preplanned comparison between connected rigid motion condition of Experiment 1 and the connected opposite motion condition of Experiment 3 revealed a significant interaction of condition by display, $F(1, 45) = 4.96$, $p < .05$: Infants showed a greater preference for the separated test display in the connected rigid motion condition of Experiment 1 than in the connected opposite motion condition of Experiment 3. The second preplanned comparison between the connected independent motion condition of Experiment 2 and the connected opposite motion condition of Experiment 3 revealed no significant interaction, $F(1, 45) = 1.53$, $p > .25$.

Discussion

The looking patterns of the infants in Experiment 3 provided evidence that infants perceived the connected opposite motion assembly as ambiguous between two separated units and a single connected unit. Moreover, the comparison of looking preferences in the opposite motion and rigid motion conditions provides evidence that rigid rotary motion specifies object unity to infants more effectively than contingent but opposite rotary motion, when infants explore objects in the haptic mode.

The contrast in infants' response to the rigid and opposite motion displays is striking, because the two patterns of motion are highly similar. In both displays, infants experienced the same paths of rotary motion from the same common fixed point. In both displays, moreover, the motions of the rings at the two hands were equally contingent. All that distinguished the two motions was the direction of rotation. Infants' differing perceptions in these two conditions therefore provided evidence that they are quite sensitive to rotary motion relationships in the haptic mode.

Nevertheless, the analysis comparing infants' perception of the connected independent versus opposite motion displays provided no evidence that these differing motion patterns influenced infants' perception. It is possible that infants failed to detect the difference in these two motion patterns. Alternatively, infants may have perceived that the rings moved differently in these two conditions, but this difference may not have affected their perception of object unity.

GENERAL DISCUSSION

The present experiments are the first to provide evidence that young infants perceive object unity from rotary motion patterns. Their findings suggest that all rigid displacements—rotations as well as translations—are potentially informative to infants, at least in the haptic mode. More specifically, the experiments investigated how infants' perception of object unity is influenced by three spatio-temporal properties of rotary motion: (1) the presence or absence of a common fixed point of rotation, (2) the presence or absence of a common pattern of rigid displacement, and (3) the presence or absence of a contingent motion. Infants' perception was influenced by the rigidity of rotary motion: When two haptically presented rings moved rigidly together, they were perceived as a single, unitary object. The presence or absence of a fixed point of rotation also exerted a marginally significant influence on infants' perception: Perception of object unity was stronger when the rings rotated around a single fixed point. Finally, independent and opposite motions from a single fixed centre of rotation appeared to have equivalent effects on perception of object unity: In both cases, infants perceived the rings as distinct, separated objects.

Although previous experiments provide evidence that translatory motion patterns have the same effects on infants' object unity in the visual and the haptic modes (e.g., Kellman & Spelke, 1983; Streri & Spelke, 1988), the present findings suggest that the effects of rotary motion are different in the two modes. In Kellman (1993) and Eizenman and Bertenthal's studies (1998), 4-month-old infants showed no ability to perceive a unitary object in the visual mode when the object underwent either a continuous or an oscillating rotation. In contrast, 4-month-old infants in the present experiments clearly perceived a unitary object in the haptic mode when the object underwent a unitary rotation that was either continuous or oscillating, depending on the infant's active manipulation. Comparisons between infants' perception of rigidly rotating objects, oppositely rotating objects, and independently rotating objects revealed that perception of object unity in the haptic mode depended specifically on detection of a unitary rigid rotation. How could we explain the different results obtained with the visual and haptic rotating displays?

Two differences between the visual and haptic displays could account for infants' differing performance in the two modes. First, it is possible that the rigidity of a unitary rotary motion is perceived better in the haptic mode because the infant actively produces the motion and experiences the common forces that the two ends of the moving object exert upon each other. In visual studies, in contrast, infants only observe the motions produced by others and have no opportunity to produce those motions or experience the resultant forces. A second possible explanation follows from the analyses of Eizenman and Bertenthal (1998). In experiments testing infants' perception of object unity in the visual mode, infants were presented with an object that rotated about an axis at its occluded centre, such that its ends moved in opposite directions. In our experiments, in contrast, infants were presented with an object that rotated about an eccentric axis, such that its two tangible ends moved in the same direction. It is possible that this difference, rather than any difference between the visual and haptic modalities, accounts for the differing findings of the studies.[1] To distinguish these two possibilities, future research would need to investigate either haptic perception of objects that rotate rigidly

[1]We thank an anonymous reviewer for suggesting this explanation.

about their midpoint, or visual perception of objects that rotate about an eccentric axis. Such research may bring considerable insight into the developing processes of object perception.

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APPENDIX

Adults (10 women and 5 men ranging in age from 25 to 38 years, M = 27 years) were presented with the four assemblies of Experiments 1–3 as well as a haptic assembly used in the experiments of Streri and Spelke (1988) and consisting of two wooden rings of the same dimensions as those in the present assemblies, connected by a 200 mm wooden bar that constrained them to move rigidly together (Figure 1e, p. 526).The adults were blindfolded and handed the rings to explore for 10 s. The five assemblies were presented in a different Latinized order (3 subjects for each order). After presentation of each assembly adults were asked, in order, about the perceived object unity ("Does what you are holding feel like one object or two objects?") and the perceived connectedness of the rings ("Does what you are holding in your left hand feel connected to what you are holding in your right hand?"), in each case rating their perception on a 7-point scale. Then they were asked to draw the complete assembly. Drawings were rated for accuracy by an assistant who was not present at the time of the experiment and was unaware of its hypotheses, and who rated on a 7-point scale the resemblance of each drawing to each of the five assemblies.

Ratings for each drawing and assembly were compared to the mean rating for that drawing by two-tailed t tests. Every drawing was rated as more similar to the correct target display than one would expect by chance (Table A1). Ratings of the unity and connectedness of the different displays were compared via one-way ANOVAs (Figure A1, overleaf). There was a significant effect of display on perception of object unity, $F(4, 56) = 30.53$, $p < .001$, and on perception of object connectedness, $F(4, 56) = 28.11$, $p < .01$. Tukey HSD tests revealed that judgements of unity and connectedness were significantly lower for unconnected than for connected assemblies and for the nonrigid motions than for the rigid motions (all ps < .01). Adults' perception of the ring assemblies therefore was accurate, and adults' judgements of object unity and connectedness were reliably influenced by the spatial and kinematic relationships tested with infants.

TABLE A1
Mean similarity ratings for adult subjects' drawings

Drawing	*a*	*b*	*c*	*d*	*e*	*mean*
a	8.73***	1.33	2.13	1.67	1	2.97
b	1.27	8.47***	6.13	4.07	1.47	4.28
c	1.73	4.53	8.20***	4.40	1	4.96
d	1.47	5.87*	6.73***	6.07**	1	4.22
e	1.00	1.93	2.13	1.67	8.07***	2.96

*p < .05; **p < .01; ***p < .001.

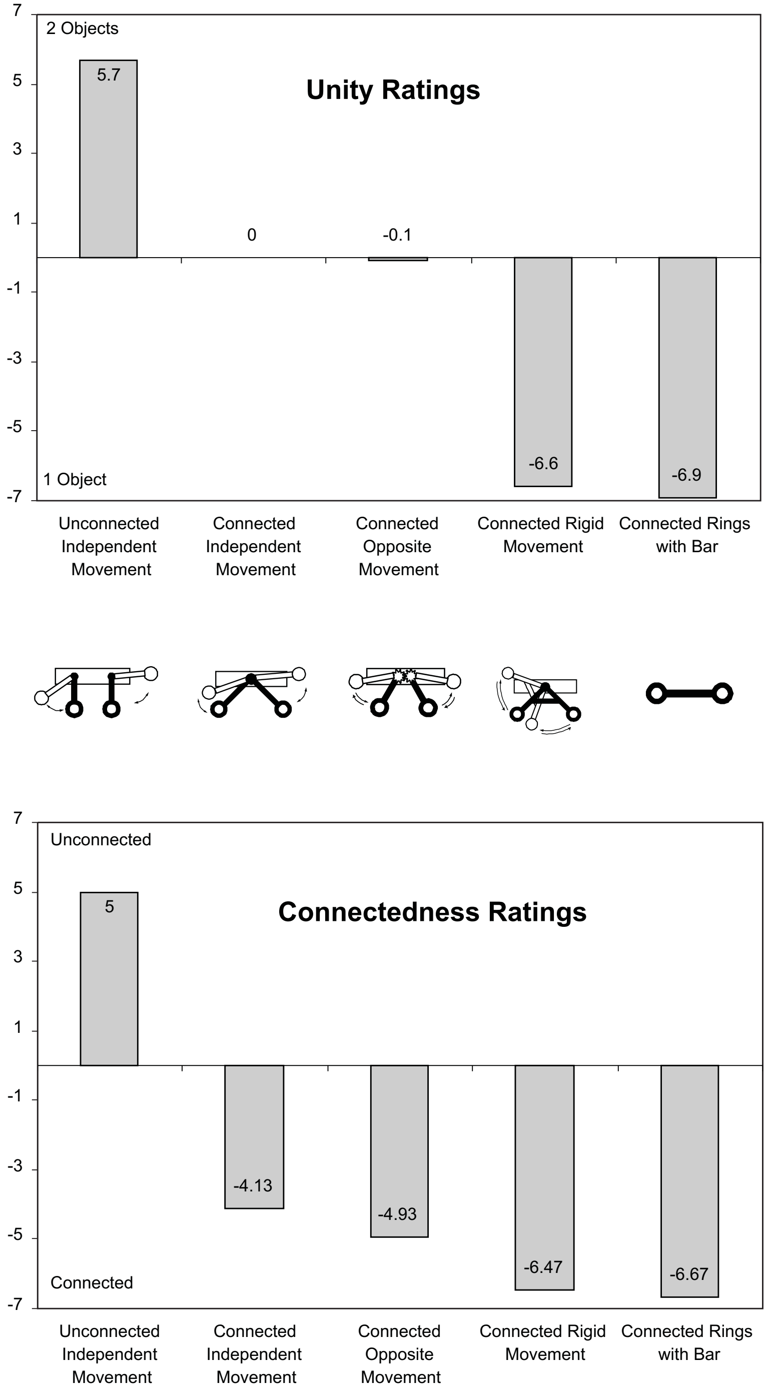

Figure A1. Ratings of object unity and surface connectedness for the five haptic displays by the adults' experiment.