Mark A. Schmuckler
Derryn T. Jewell
Department of Psychology, University of Toronto at Scarborough, Scarborough Ontario, Canada M1C 1A4
E-mail: marksch@utsc.utoronto.ca

Infants' Visual-Proprioceptive Intermodal Perception With Imperfect Contingency Information

***ABSTRACT:** Two experiments explored 5-month-old infants' recognition of self-movement in the context of imperfect contingencies between felt and seen movement. Previous work has shown that infants can discriminate a display of another child's movements from an on-line video display of their own movements, even when featural information is removed. These earlier findings were extended by demonstrating self versus other discrimination when the visual information for movement was an unrelated object (a fluorescent mobile) directly attached to the child's leg, thus producing imperfect spatial and temporal contingency information. In contrast, intermodal recognition failed when the mobile was indirectly attached to infants' legs, thus eliminating spatial contingencies altogether and further weakening temporal contingencies. Together, these studies reveal that even imperfect contingency information can drive intermodal perception, given appropriate levels of spatial and temporal contingency information. © 2007 Wiley Periodicals, Inc.* Dev Psychobiol 49: 387–398, 2007.

Keywords: *intermodal perception; visual-proprioceptive recognition; infant development*

INTRODUCTION

In daily life individuals are barraged with information arising from multiple perceptual systems. Rather than experience this wealth of information as unconnected perceptual inputs, however, these varying sources are perceived as coherent wholes, forming unified percepts of objects and events, a process known as "intermodal perception" (Spelke, 1987). Understanding how such multiple inputs are coordinated has been of interest to psychologists for some time. Currently, a great deal of evidence attests to the early development of intermodal perception (for reviews, see Bushnell & Boudreau, 1991, 1993; Lewkowicz, 2000, 2001; Lewkowicz & Lickliter, 1994; Lickliter & Bahrick, 2000, 2001; Rose & Ruff, 1987), with neonates even demonstrating a form of intermodal coordination via their visual localization of an auditory sound source (Muir & Field, 1979). Generally, there is agreement that visual-auditory intermodal perception is present with the first few months (Bahrick, 1988, 2001, 2002; Bahrick, Flom, & Lickliter, 2002) and possibly even earlier (Sai, 2005), and that visual-tactile intermodal relations are operative by about 5 months of age (Bushnell & Boudreau, 1991, 1993; Rose & Ruff, 1987).[1]

Received 16 February 2006; Accepted 9 December 2006
Correspondence to: M. A. Schmuckler
Contract grant sponsor: Natural Sciences and Engineering Research Council of Canada

[1] Reports of visual-tactile intermodal perception by much younger infants (i.e., neonates to 1-month-old), such as Gibson and Walker (1984), Kaye and Bower (1994), and Meltzoff and Borton (1979), have come under attack in recent years (Maurer, Stager, & Mondloch, 1999). Given the extremely careful failure to replicate Meltzoff and Borton's (1979) results by Maurer et al. (1999), and the somewhat obvious conceptual and procedural flaws of Kaye and Bower (1994), this leaves only the classic study by Gibson and Walker (1984) as unassailable evidence of intermodal perception in very young infants. As such, a conservative conclusion might be that the visual-tactile intermodal abilities of infants younger than 5–6 months are, at best, unclear.

Investigating intermodal relations has not been limited to perceptual system functioning, however. Issues concerning the intermodal integration of perceptual (such as visual, auditory, or haptic) and vestibular and/or proprioceptive sources (Schmuckler, 1995, 1996b) are also of interest. Along with a variety of indirect evidence for such intermodal knowledge, such as arises in work on spatial orientation (Jewell & Schmuckler, 2000; Schmuckler & Tsang-Tong, 2000), postural control (Bertenthal & Bai, 1989; Bertenthal, Rose, & Bai, 1997; Schmuckler & Gibson, 1989; Stoffregen, Schmuckler, & Gibson, 1987), and visually guided locomotion (Catanzaro & Schmuckler, 2002; Kingsnorth & Schmuckler, 2000; Schmuckler, 1996a), intermodal coordination of visual and proprioceptive inputs has also been the subject of direct experimental investigation. Bahrick and Watson (1985), for instance, explored visual and proprioceptive intermodal perception in 5-month-old infants by hiding infants' legs while presenting an on-line video display of this leg movement paired with a prerecorded video display of another child's leg movements. Such a situation thus creates one visual display that matches the proprioceptive information of the hidden limbs (called a "contingent display") and a second display that diverges both temporally and spatially (called a "noncontingent display"). Infants in this study differentially fixated the two displays, a result interpreted as indicating perception of the visual-proprioceptive contingency relations between the displayed leg movements and infants' sensations of movement. Interestingly, and somewhat counter-intuitively, infants' preferential fixation was toward the noncontingent display rather than toward the contingent display, a finding consistent with previous related studies (e.g., Papousek & Papousek, 1974).

Subsequent research, by multiple authors, has extended these initial findings. One avenue of exploration has examined the role of spatial and temporal contiguity in such intermodal perception. Both Rochat and Morgan (1995) and Schmuckler (1996b) for instance, replicated Bahrick and Watson's (1985) original result, and extended it by demonstrating that spatial contiguity was critical for intermodal perception in such situations. Specifically, both studies found that reversing left–right spatial relations, such that a physical movement to the left appeared visually as a movement of the limb (either a hand or the legs) to the right, disrupted intermodal perception. Interestingly, this failure of intermodal perception occurred despite the presence of temporal contingencies between visual and proprioceptive inputs, thus demonstrating that temporal contingencies in and of themselves (and in the presence of varying spatial information) are insufficient to drive intermodal perception. Looking more directly at the importance of temporal information, Rochat and Striano (2002) found that 4- and 9-month-olds reactions to an on-line image of themselves and a temporally delayed (by 2 s) image of themselves were highly similar in their exploratory (e.g., the length of time looking) and social (e.g., the amount of smiling) characteristics.

The importance of featural information in such intermodal perception has also been explored. Morgan and Rochat (1997) and Rochat (1998), for instance, found that 3- to 5-month-old infants failed to demonstrate visual-proprioceptive intermodal perception when their legs were covered with puffy leggings, thereby eliminating familiar featural characteristics of their own limbs. These leggings, however, not only obscured featural information, they may have also masked some of the actual movement itself, with the decreased visual motion possibly underlying this failure of intermodal perception. In contrast, Schmuckler and Fairhall (2001) did find that point-light displays of leg movements were sufficient to drive 5- and 7-month-old infants' intermodal perception, provided that such movement occur within a context of a familiar, ego-centered view. When presented devoid of this familiar context, or from an observer-centered view, this motion information was insufficient to drive visual-proprioceptive intermodal perception.

Other researchers have confirmed the importance of motion information in visual self-perception more generally. Using prerecorded videotapes of their own face versus another child's face, Bahrick, Moss, and Fadil (1996) found that even young infants (e.g., 3- to 5-months) showed self-perception when these faces were presented dynamically, but not statically (see also Legerstee, Anderson, & Schaffer, 1998). And Rochat and Striano (2002) found that from 4-months onwards infants react differently when viewing their face as opposed to the face of a mimicking other, suggestive of self-perception. Together, all these findings highlight the importance of spatially congruent motion information for self-perception.

A final avenue of investigation has examined intermodal coordination as it functions in self-exploration and exploration of the environment. Rochat and Morgan (1998), for instance, found intermodal perception by 3- to 6-month-old infants in a condition in which leg movements produced a sound, as well as when a sound producing target object was present. Intriguingly, whereas intermodal perception was demonstrated by preferential fixation of the noncontingent display in the first condition (the typical result), preferential looking reversed in the second condition, with infants looking significantly longer at the contingent display of their own legs. According to these authors, this reversal occurred due to the goal-directed nature of the infants' movements. Finally, Rochat and Striano (1999) found that

2-month-old infants (but not newborns) modulated their sucking pressure on a pacifier when this pressure was contingent with variations in the pitch of a tone, but not when sucking pressure was unrelated to pitch changes. Taken together, these findings suggest that within the first year of life infants have an (intermodal) sense of their own body, and a sense of self-agency, and can control or monitor their activity to either explore themselves or to explore the world.

One component common to virtually all of this work (except for Rochat & Striano, 2002, discussed subsequently) is that there is a perfect 100% correlation between proprioceptive information and the visual information (e.g., Bahrick & Watson, 1985; Rochat, 1998; Rochat & Morgan, 1995, 1998; Schmuckler, 1996b; Schmuckler & Fairhall, 2001), or between oral-tactual and auditory information (Rochat & Striano, 1999). Much more common, however, would be situations of imperfect contingencies in which the correlation between one's movement and the visual (and possibly physical) consequences of that movement are not 100% related.

Developmentally, distinguishing between perfect and imperfect contingency information is, in fact, a likely critical step in the child's development of self-other distinctions. Perfect contingencies will (barring extraordinary mimicry situations) only occur for movements of the self. In contrast, imperfect contingencies arise in multiple situations, including self-movements that are somehow nonrigid (this idea will be developed subsequently), as well as in causal self-other interactions with both persons and objects. In fact, the distinction between perfect and imperfect contingencies has been considered to be critical for distinguishing between self and other (Bahrick & Watson, 1985; Watson, 1972, 1979, 1985, 1994, 1997, 2001), as well as in understanding social interaction between parent and child (Bigelow, 1998, 2001; Bigelow & Birch, 1999; Bigelow & DeCoste, 2003; Rochat, 2001a, 2001c; Rochat & Hespos, 1997), with differences in imperfect social contingencies potentially playing a role in infant attachment (Bigelow, 2001; Watson, 2001) and evident in the social interaction patterns of depressed mothers (Bigelow, 2001; Bigelow & DeCoste, 2003; Field, 1987). Given all of this, it is of significant interest to understand how infants process imperfect contingencies.

Although there is a great deal of research on infants' understandings of contingency relations within the context of learning and memory (see Rovee-Collier & Barr, 2001, for a review), little work has explored this question within the framework of intermodal perception. The only exception to this rule is an unpublished series of studies by Flom and Bahrick (2001), who investigated 5-month-old infants' abilities to detect the visual-proprioceptive intermodal relations of a point light display of their own legs along with an attached appendage on which there were additional point lights. Because these appendages were not rigidly attached to infants' calves, appendage movements differed spatially, and often lagged behind, leg movements, thus providing imperfect spatial and temporal contingencies between visual and proprioceptive inputs. Nevertheless, infants in this study preferentially fixated the noncontingent display, demonstrating that even imperfect contingencies can lead to self-perception.

Although suggestive, Flom and Bahrick's (2001) results are limited in a few ways. Most importantly, because the point lights were simultaneously located on both the legs and the appendages, the point lights on the legs were perfectly contingent whereas the point lights on the appendages were imperfectly contingent. Thus, along with providing an uncontrolled mixture of perfect and imperfect contingency relations, it was also possible that intermodal perception occurred through infants' focusing on the perfect contingency information. Hence, the efficacy of imperfect contingency information in intermodal perception remains open.

Two experiments, then, explored the question of infants' intermodal perception of imperfect contingency information. In the first, imperfect contingencies were created by attaching a glow-in-the-dark mobile directly to infants' unseen legs. Because this mobile was nonrigid, the contingency information, although roughly congruent spatially and temporally, was less than perfect. In the second study, spatial and temporal contingencies were made even more abstract by yoking the mobile to leg movement via a string and pulley. In both studies, self-perception was tested by looking for preferential fixation to an on-line (a live visual presentation) versus an off-line (a previously recorded videotape) display of the mobile.

EXPERIMENT 1

Intermodal Perception of a Moving Mobile Appendage

The purpose of this study was to determine whether the visual-proprioceptive intermodal perception abilities found in previous work (Bahrick, 1995; Bahrick & Watson, 1985; Morgan & Rochat, 1997; Rochat, 1998; Rochat & Morgan, 1995, 1998; Schmuckler, 1996b; Schmuckler & Fairhall, 2001) could be evidenced in situations in which there were imperfect spatial and temporal contingency relations between visual and proprioceptive inputs. To test this, an infant observed two visual images. The first, or contingent display, was an on-line presentation of a mobile attached to his or her moving leg, whereas the second, or noncontingent display, was an off-line previously recorded videotape of the mobile attached to another child's leg. As in previous studies, detection of intermodal visual-proprioceptive contingencies should result in preferential fixation of the noncontingent (i.e., off-line) display.

In such a situation, the visual and proprioceptive information remain related in at least two ways. First, the temporal contingencies remain in place for the top section of the mobile that was directly attached to the child's leg, although this relation is not retained for the remaining segments of the mobile. Second, spatial information remains relatively congruent, with, for instance, movement of the leg to the left being seen as a display that overall (and again, primarily for the top segment of the mobile) moves to the left. Accordingly, although weaker than in the previous work, both spatial and temporal contingencies are present in some form.

Method

Participants. For this study, 20 5-month-old infants (9 females, 11 males) participated, with a mean age of 20.7 weeks (range = 19.3–23.0 weeks). Thirteen additional infants began this experiment but were not used in the final analyses. Of these infants, one was removed because the parent continually talked during testing, two due to prematurity, seven due to procedural errors or technical difficulties during testing, and three because they only looked at one of the two displays in one direction on at least one trial and thus could not be said to show a "preference." All infants were recruited from the demographically diverse Scarborough, Ontario, community and received a toy and certificate for participating.

Stimuli. Two video displays were used as the stimuli for this study: one contingent and one noncontingent. The contingent display was an on-line image of a mobile that was directly attached by Velcro to the lower portion of one of the child's legs and thus, moved with the child's motions. The noncontingent display was a videotape of the mobile attached to the leg of the child who had just previously completed the experiment. Use of the videotaped record of the previous participant as the noncontingent foil has precedents in earlier research (i.e., Schmuckler, 1996b; Schmuckler & Fairhall, 2001). By having the contingent display for one participant be the noncontingent display for the next, this procedure controls for looking preferences being driven by aspects of leg movements such as speed of motion, amount of motion, and so on, given that such factors will vary naturally across infants, and hence will not align consistently with contingent or noncontingent designations.

Apparatus. The study was run in an experimental chamber covered with acoustic paneling, dimly lit by overhead spotlights. During the testing session, each infant faced a pair of Samsung (34.7 cm) CT-3312 VC color video display monitors. These monitors were placed approximately 15 cm atop of a 74.5 cm high table, separated by 20.3 cm. Orange curtains hung behind the displays prevented sight of what lay behind the monitors. An observer positioned behind these curtains focused a Sony Handycam DCR-TRV 103 video camera on the infant's face, and recorded visual fixations by pressing the left or right button on a computer mouse attached to a computer when the infant fixated the left or right display, respectively.

In front of the table with the video monitors was a 0.9 m tall, 0.8 m wide, and 0.4 m deep wooden box. This box had panels cut out of the front (the end facing the infant) and the back (the end beside the table with the monitors) and the inside was lined with black construction paper. At the back end of this box was a JVC GS-CD1U video camera, positioned such that the image produced from this camera provided an upright, left–right spatially appropriate view of the inside of the box. The inside of the box was illuminated by a blue-black lamp.

Each child wore a pair of black socks to prevent recognition of body parts. The mobile, comprised of red, yellow, and green linked fish shapes, was fluorescent and was attached to one of the child's lower legs (between the knee and ankle) using Velcro. Illuminating the mobile with the blue-black lamp, with the brightness of the monitor turned down and the contrast turned up, caused only the mobile to appear on the displays.

Figure 1 illustrates the experimental setup. The parent sat in a chair placed at a right angle to the box, facing the side wall, and the infant sat on the parent's right leg, in front of the box, facing the video monitors. In this position it was possible to place the infant's legs through the curtain into the box, such that they were hidden from immediate view. The presentation of the noncontingent display, the recording of the infant's visual fixations, and the recording of the contingent image, accomplished using a JVC HR-D570U VCR, was controlled by an experimenter in an adjacent room. The noncontingent display was presented using a JVC HR-D550U VCR, and the infant's face was recorded using a Panasonic AG-2510 VCR. Also located in this control room was an IBM-PC compatible 286 MHz computer, which kept track of trials and the timing of the visual fixations.

Procedure. Before the testing session, a parent put the black socks onto the infant's legs, either over the child's clothes or by removing shoes and rolling up long pants and pulling up the socks. The experimenter ensured the black Velcro strip on the socks was positioned appropriately, sat the parent and child in front of the wooden box, and then placed the child's legs into the front of the box. Once the

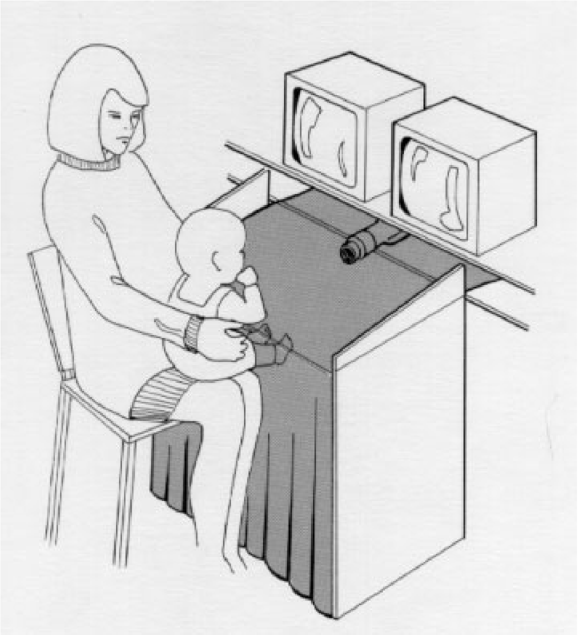

FIGURE 1 A schematic diagram of the experimental setup for Experiments 1 and 2. Note that in Experiment 1, parents actually faced the reverse direction during the study and that for Experiment 2 parents either faced the reverse direction or were positioned as shown (see text for details).

child's legs were in the box, the mobile was attached to the lower leg. Half of the infants had the mobile attached to their right leg and watched a tape of a child with a mobile on the right leg, whereas the other half had the mobile attached to their left leg and watched the corresponding prerecorded display. As in Schmuckler and Fairhall (2001), the parent was asked to gently move the infant's legs to ensure adequate (and interest sustaining) movement of the mobile. The parent was allowed to do this in any fashion but was shown as an example a simple action (a leg jump) that increased mobile movement. The parent was asked to not look at the monitors or speak to the child during the trials.

Once both parent and child were in position, the experiment began with the onset of the two stimulus displays. The contingent and noncontingent images appeared simultaneously, and visual fixations toward each monitor were recorded. After 1 min, the displays were turned off, a short break was taken if necessary, and the procedure was repeated for a second trial, with the left–right position of the contingent and noncontingent displays reversed relative to the first trial. For half the infants the contingent display appeared on the right monitor during the first trial and on the left monitor during the second trial, with the remaining infants seeing a reversed ordering. The actual testing time was very brief (about 5 min), with the entire visit to the laboratory lasting approximately 30 min.

Reliability. Because the experimental sessions were videotaped, it was possible to obtain reliability codings for these measures. Accordingly, a second observer, naïve to the experimental hypotheses and to the left–right position of the displays, also coded visual fixations for both trials for 19 of the 20 infants (one child only provided one trial for reliability due to a cut-off video recording). Two criteria were employed for determining if fixation codings were reliable. First, a coding was considered unreliable if the difference between the original and reliability changed the pattern of preferential looking (e.g., more looking to the contingent display in the original, but the reverse pattern for the reliability); this criterion has been used in previous work (Schmuckler, 1996b; Schmuckler & Fairhall, 2001). Second, the percentage difference was calculated for each pair of codings for total fixation (larger looking time-smaller looking time/smaller looking time), with a difference greater than 30% considered unreliable. Given that only one pair of codings from three infants exceeded this difference,[2] and that none of these infants violated the change in preferential fixation criterion, data from all participants were considered reliable. The mean absolute difference between the two sets of codings of total fixation, averaged across left/right displays and the experimental trials, was 1.2 s (SD = 1.2 s). Aggregating across trial and left/right displays, the two codings of total fixation were strongly correlated, with $r(78) = .99$, $p < .001$.

Results and Discussion

For each infant, the proportion of total fixation toward the two displays was computed by dividing the time spent looking toward either display by the total time spent looking toward both displays. The proportional total fixation scores were then turned into difference scores by subtracting the proportion of time spent looking toward the contingent display from the proportion of time spent looking toward the noncontingent display. Accordingly, positive difference scores reflect preferential fixation of the noncontingent display, whereas negative scores indicate preferential fixation of the contingent display. A two-way analysis of variance (ANOVA), with the between subjects factor of *order* (contingent on the left side in trial 1 vs. contingent on the right side in trial 1), and the within subjects factor of *trial* (trial 1 vs. trial 2) was computed on these difference scores. This analysis revealed a main

---

[2] It should be noted that in this study, and in the subsequent Experiment 2, the infants who did produce reliability coding differences of greater than 30% all had extremely short (i.e., less than 10 s) looking times. Given such short looking times, even relatively small differences in reliability coding can produce large percentage differences. This is why, in fact, we employ a two-pronged criterion for determining reliability.

effect of trial, $F(1,18) = 12.59$, $\mathrm{MSE} = 0.12$, $p < .005$, no effect of order, $F(1,18) = 0.67$, $\mathrm{MSE} = 0.28$, n.s., and no interaction between the two, $F(1,18) = 0.06$, $\mathrm{MSE} = 0.12$, n.s. Because the analyzed values are difference scores, the trial effect indicates that the preferential fixation toward the two displays varied across the trials, with a larger difference score on trial 1 ($M = .20$, $SD = .37$) than on trial 2 ($M = -.19$, $SD = .50$).

Subsequent exploration of this trial effect was accomplished by comparing the difference scores for each trial to zero, which represents 50% looking toward each display (and thus no preference). Infants demonstrated significant preferential fixation of the noncontingent display on trial 1, $t(19) = 2.39$, $p < .05$, but not on trial 2, $t(19) = -1.71$, n.s. The proportion looking toward the contingent and noncontingent displays on both trials appears in Figure 2, and indicates intermodal perception on the first but not the second trial.[3] Individually, 15 of 20 infants displayed a preference for the noncontingent display on trial 1, whereas only 9 of 20 infants showed this preference on trial 2. This first value is significant according to a sign test ($p < .05$), whereas the second is not. Note that this difference cannot be attributed to a simple side bias. Of the 20 participants, 4 showed a clear bias in looking (e.g., a difference of greater than 5 s in looking toward one or the other side on both trials). When the just described two-way ANOVA was recalculated after removing these four infants, similar findings were observed. Moreover, a subsidiary test, using total looking time (in seconds) to both contingent and noncontingent displays failed to find any differences in looking as a function of side, $t(19) = -.046$, n.s., demonstrating there were no general side biases.

Given its concurrence with previous studies (e.g., Bahrick & Watson, 1985; Morgan & Rochat, 1997; Rochat & Morgan, 1995, 1998; Schmuckler, 1996b; Schmuckler & Fairhall, 2001), the preferential fixation of the noncontingent display on the first trial suggests intermodal perception. This result is noteworthy in that such recognition occurred without any featural information for the leg itself (replicating Schmuckler & Fairhall, 2001) and most importantly, with imperfect spatial and temporal contingency relations between visual and proprioceptive inputs, thus converging with Flom and Bahrick's (2001) unpublished results.

Of course, this study also raises questions concerning why self-perception disappeared on the second trial, and how to interpret this lack of preferential looking. In this regard, it is noteworthy that previous research has found self-perception to be stronger at the beginning of an experimental session. Bahrick et al. (1996), for instance, found that infants' discrimination of a prerecorded videotape of their own face from the face of a peer was more robust in an initial block of trials than in subsequent trials.

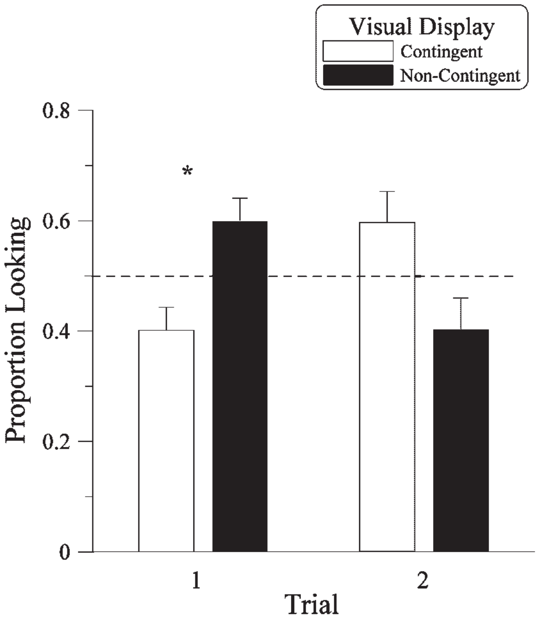

FIGURE 2 Proportion looking times toward the contingent and noncontingent displays of Experiment 1, as a function of trial. Chance (50%) is shown as a dotted line, with the asterisk indicating that these proportions differ significantly from chance.

Additionally, it is also important to consider what factors may have differed between the trials of this experiment, and hence have led to the disappearance of preferential fixation in the second trial. One possibility involves variation in the amount of infant leg movement produced by the parent. As described initially, parents gently moved their child's leg, with this instruction repeated between the two trials. Our informal observations suggest that, because we repeated this instruction, many parents actually increased the amount of leg movement on trial 2 relative to trial 1. Unfortunately, given the nature of our experimental apparatus we are unable to test this hypothesis directly.[4]

Why would increased leg movement have modified preferential looking? One explanation is that, due

---

[3] In addition to the proportion of total fixation, the number of fixations in a particular direction and the duration of the first look to each direction were recorded. These data did not provide any significant effects, although the pattern of looking was similar to that obtained for total fixation time. For simplicity, only data from the proportional times will be presented.

[4] Although leg movements were recorded to be presented as the noncontingent display for another participant, no markers are evident on the videotape to indicate trial start and end. Therefore, the trials cannot be differentiated in order to contrast movement and confirm that movement indeed was greater on the second trial.

to the imperfect contingencies between vision and proprioception, increased leg movement may have made the less than perfect spatio-temporal linkages more salient to infants, with this increased salience having one of two consequences. First, this increased salience might simply have made it more difficult to extract the contingency information required to discriminate self from other, an explanation in line with earlier work showing that manipulating left–right spatial relations (Rochat & Morgan, 1995; Schmuckler, 1996b) or egocentric versus other viewpoints of point light displays (Schmuckler & Fairhall, 2001) eliminates intermodal perception.

Second, the increased salience of visual-proprioceptive relations may have actually increased children's interest in the display of their own movement. Along these lines, infants' increased interest in their own image may be due to the actual movements themselves being outside the range of their own typical movement (e.g., variation in, say, speed and amplitude of leg movements), or to an increased experience of passive relative to active leg motions. Such differences might then arouse infants' interest through a concern with understanding the agency underlying these changes, resulting in more attention to self in such a situation. Although admittedly speculative, this idea does fit with Morgan and Rochat's (1997) finding that infants reversed their preferential fixation when there was a target object that made a sound when kicked. Thus, situations emphasizing (and rewarding) self-exploration led to an increased interest in contingent, as opposed to noncontingent, displays.

As an aside, the idea that the data for trial 2 actually reflect a burgeoning preference for self-movement caused by infants' interest in exploring the forces underlying any perceived motion variation leads to the prediction that infants will shift their preference from noncontingent to contingent displays when leg movements are generated actively (by infants) versus passively (by parents), respectively. Moreover, more careful manipulation of passive movements by parents would allow for testing the role of ''typicality'' of leg movements, with the shift in preferential fixation possibly occurring at the point at which limb movement exceeds that which infants can normally produce themselves. Research into such predictions would be an interesting test of these hypotheses.

Regardless of the interpretation of preferential fixation data for trial 2, this study does demonstrate perception of self-movement on the basis of the imperfect spatial and temporal visual and proprioceptive contingency information. Experiment 2 extended these findings, using displays that further modified the strength of the contingencies between these two sources of information.

EXPERIMENT 2

Intermodal Perception of a Spatially Fixed Mobile Appendage

Experiment 1 retained some degree of spatial and temporal contingency information between visual and proprioceptive inputs, and demonstrated a level of intermodal perception. Experiment 2 extended these findings by further weakening the temporal contingencies, and eliminating spatial relations altogether. This was accomplished by yoking mobile movement to the child's leg movement by means of a string looped around the child's legs and attached to a stationary mobile through a pulley (see Fig. 3). As a consequence of this pulley/string design, mobile movement was now primarily vertical with slight horizontal movements, and contained a randomly varying temporal delay due to the lack of rigidity in this system. Accordingly, this arrangement degraded temporal contingencies even further, and eliminated spatial contingencies altogether, although it did not provide conflicting spatial information (i.e., movement of the leg to the left appeared as movement to the right) as has occurred in previous work.

Method

Participants. Twenty 5 month-old-infants (8 males, 12 females) participated, with a mean age of 21.1 weeks (range = 19.0–23.7 weeks). Seven additional infants began this experiment but were omitted from the final analyses. Of these seven infants, one was excluded due to prematurity, three due to procedural error or technical difficulties at the time of testing, and three because they only looked in one direction on at least one trial. All infants were recruited as in Experiment 1, and received a toy and certificate for participating.

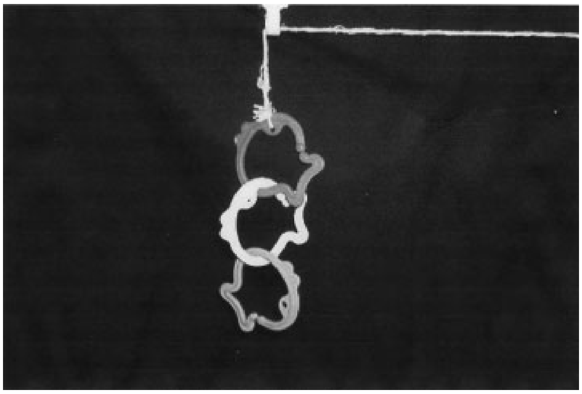

FIGURE 3 The pulley/string apparatus used in Experiment 2 (string was not visible to the participants, but is shown here for demonstration purposes).

Stimulus, Apparatus, Procedure, and Reliability. As in Experiment 1, the stimuli consisted of an on-line contingent display of the mobile attached to the infant's leg, and a videotaped noncontingent display of the previous participant's mobile movement. The study was run with the same equipment as Experiment 1, with the following exceptions. Instead of the mobile being attached directly to the child's limb, it was attached via a string looped around the infant's knee. The string was held in place with a small pulley, attached underneath the top of the box, such that the mobile dangled and moved vertically, with slight horizontal movements. The pulley was positioned approximately 15 cm from the side of the box so as to not constrain leg movement, and was placed on the right side of the box when the string was attached to the right leg, and on the left side of the box when the string was attached to the left leg. Because of this pulley/string arrangement, it was necessary to have the infant sit on the parent's right leg when the mobile was attached to the right leg, and on the left leg when the mobile was attached to the left leg, hence requiring a shift in the parent's orientation. Once positioned, and before the experimental trials started, the parent was asked to move the infant's leg in the same manner as in Experiment 1 and practiced this movement with the monitors off before testing began.

A second observer who was naïve to the location of the contingent and noncontingent displays performed reliability codings on the looking time toward the two monitors using the videotaped recordings of the trials. Based on reliability calculated for all 20 infants (one trial was unavailable for one infant), all looking time data were deemed reliable. Although one pair of codings from two infants exceeded the cut-off of 30% difference in looking times, the preferential looking patterns were the same for both sets of codings for these infants. The mean absolute difference between the two sets of codings, averaged across left/right displays and the experimental trials, was 1.2 s (SD = 1.1 s). Aggregating across trial and left/right displays, the two sets of fixations were strongly correlated, $r(78) = .99$, $p < .001$.

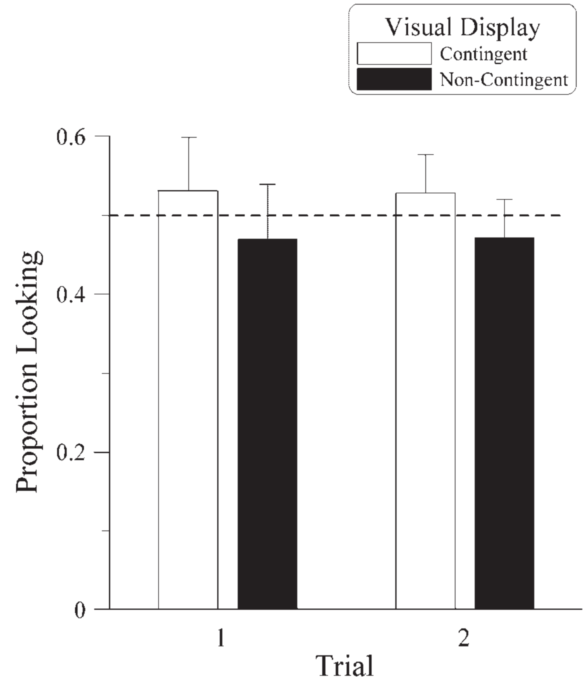

FIGURE 4 Proportion looking times toward the contingent and noncontingent displays of Experiment 2, as a function of trial. Chance (50%) is shown as a dotted line.

Results and Discussion

Difference scores were computed as in Experiment 1 (noncontingent minus contingent) and were analyzed using a two-way ANOVA, with the between subjects factor of *order*, and the within subjects factor of *trial*. This analysis failed to reveal a main effect for trial, $F(1,18) = .00$, MSE = 0.34, n.s., or for order, $F(1,18) = 0.34$, MSE = 0.24, n.s., or any interaction between the two factors, $F(1,18) = 1.22$, MSE = 0.34, n.s. For comparison with Experiment 1, Figure 4 displays the proportion looking times toward the contingent and noncontingent displays as a function of trial, and illustrates that infants failed to demonstrate any preferential looking whatsoever. This failure of preferential fixation was confirmed statistically by testing the difference scores for trial 1, trial 2, and an averaged trial 1 and 2, against zero. None of these tests revealed a significant difference, all t's$(19) < 1.0$. For trials 1 and 2, 9 and 10 infants showed a preference for the noncontingent display, respectively, neither values being significant according to a sign test.

Follow-up analyses failed to reveal differences in total fixation time (in seconds), combining across contingent and noncontingent displays, toward the left or right monitors, $t(19) = 1.13$, n.s., indicating that there were no consistent side biases in looking. Individually, however, infants frequently did demonstrate a left or right side bias in their looking, with 12 of 20 infants fixating one side over the other for more than 5 s on both trials. Such side biases are quite typical of looking patterns in preferential looking when infants fail to differentiate the displays.

The most straightforward interpretation of these results is that further disruption of the spatial and temporal contingencies eliminated infants' visual-proprioceptive intermodal perception. Given the weakening of temporal contingencies and elimination of spatial contingencies in these displays, such a finding is not surprising. Previous work does demonstrate that modifying such parameters significantly impacts infants' abilities to detect visual-proprioceptive intermodal relations.

GENERAL DISCUSSION

Overall, these studies demonstrate that, under certain conditions, 5-month-old infants can perceive their own movements visually even when the correlation between visual and proprioceptive inputs is severely degraded. Clearly, one of the key components for such intermodal perception is some level of spatial contiguity. When spatial relations were unavailable, as in Experiment 2, intermodal perception failed. Such findings are very much in line with Schmuckler (1996b) and Rochat and Morgan's (1995) reports that spatial congruence was a prerequisite for intermodal perception of visual and proprioceptive inputs, as well as findings suggesting that recognition of featural information, or even a conceptually familiar object (e.g., the category of a leg) is not necessary for intermodal perception (e.g., Bahrick & Watson, 1985; Flom & Bahrick, 2001; Rochat & Morgan, 1995; Schmuckler & Fairhall, 2001) as long as these displays retain spatial contiguity.

Does this mean that temporal contingency plays a lesser role in such intermodal perception? Although it is tempting to argue this position, such an argument is not totally convincing. First, it must be remembered that the manipulations of Experiment 2 modified both spatial and temporal contingencies; hence, the failure of intermodal perception may have been due to the degradation in either (or both) dimensions. Moreover, and more generally, although an emphasis on spatial relations may be justified by the multiple demonstrations of a failure of intermodal perception even with temporal contingency (in this and other studies), definitive evidence for such an argument requires an explicit demonstration of visual proprioceptive intermodal perception of spatially congruent, temporally incongruent displays. Rochat and Striano (2002) provided some relevant evidence in their demonstration that 4- and 9-month-olds did not react differentially to an on-line versus temporally delayed image of their own face, although such findings are not conclusive given that these authors did not employ the preferential looking procedure used in other studies and because this study tested facial recognition, which is an extremely familiar, and some might argue special, stimulus (e.g., de Haan, Humphreys, & Johnson, 2002; Johnson, Dziurawiec, Ellis, & Morton, 1991; Morton & Johnson, 1991).

Given the critical role of spatial and temporal contiguity in perceiving visual-proprioceptive intermodal relations, one might wonder why we would even harbor the expectation that infants would form an intermodal link between proprioceptive and visual inputs in either of these studies. It is important to remember, however, that despite the manipulations of spatial and temporal relations in these studies, visual and proprioceptive inputs were nevertheless conjugately related in both experiments. Indeed, there is a great deal of research by Rovee-Collier and her colleagues (e.g., Bhatt, Wilk, Hill, & Rovee-Collier, 2004; Hartshorn & Rovee-Collier, 2003; Hildreth, Sweeney, & Rovee-Collier, 2003; Rovee-Collier & Barr, 2001; Rovee-Collier & Gekoski, 1979; Rovee & Rovee, 1969; Wilk, Klein, & Rovee-Collier, 2001, for classic and more recent reviews) suggesting that even very young infants are sensitive to conjugate relations in learning and memory contexts.

Intriguingly, Rovee-Collier and colleagues' well-known experimental apparatus likely produces temporal and spatial contingencies that are more similar to Experiment 2 than Experiment 1. Temporally, because the mobile in Rovee-Collier's work is attached with a nonrigid ribbon, there will be time delays and imperfect contingencies between leg and mobile movements. Spatially, because the mobile hangs from a fixed location in space above infants, leg kicks in any particular direction will not necessarily produce mobile movements that move in the exact same way and direction. Given this relation to Experiment 2, the obvious question that arises is why infants apprehend the conjugate relations in Rovee-Collier's studies, but do not perceive the intermodal correspondences in the current research. Although it is difficult to fully answer this question, the obvious methodological and procedural differences between these two lines of work, such as the use of preferential looking versus an operant conditioning technique, the length of the training phases/trials, differences in the availability of simultaneous visual and proprioceptive information, and so on, clearly plays some role here. And, in fact, Wilk et al. (2001) demonstrated that such methodological differences are critical. In a comparison of visual preference and operant-conditioning techniques, infants showed evidence of more sophisticated abilities using operant-conditioning methods than they did in a preferential looking paradigm.

Along with these distinctions, though, it is also important to remember that these two avenues of work have very different goals and explore radically different capabilities. The conjugate reinforcement paradigm quite effectively explores infants' abilities to learn about and remember conjugate relations, based on particular levels of exposure, delay times, reminders, and so on. The current work, however, is not about learning, but instead about infants' abilities to integrate perceptual and motor systems into a unified percept. It is an open question as to whether or not infants could learn about the visual and proprioceptive correspondences investigated in this work, and if so, how long they would retain this knowledge.

Characterized in this fashion, the present studies have more than a passing relation to work on the perception of arbitrary intermodal relations, such as the learned link between specific faces and voices (Bahrick, Hernandez-Reif, & Flom, 2005) or the shape of an object and its color (Hernandez-Reif & Bahrick, 2001), as well as the learning of intermodal relations more generally (Bahrick, 1988, 1994, 2002; Bahrick & Pickens, 1994; Gogate & Bahrick, 1998). In fact, this work might be seen as occupying a middle-ground position between intermodal relations that consist of specific, exact contingencies, such as in classic intermodal studies (e.g., Gottfried, Rose, & Bridger, 1977; Rose, 1990; Rose, Feldman, Futterweit, & Jankowski, 1998; Rose, Gottfried, & Bridger, 1981a,b, 1983; Rose & Ruff, 1987) and truly arbitrary intermodal linkages (e.g., Bahrick, 1994; Bahrick et al., 2005; Bahrick & Pickens, 1994; Gogate & Bahrick, 1998). What makes this work an intermediary between these two extremes is the recognition that, in these studies, movement of the limb caused the occurrence of a visual event in the world that had movement parameters (e.g., tempo, amplitude, and spatial characteristics) that were linked to, but not isomorphic with, the proprioceptive event. As such, recognizing the relation between visual and proprioceptive inputs was as much perceptual (noting synchrony in various movement parameters) as it was conceptual (inferring causality between proprioceptive and visual movements that did not share exact properties).

Finally, it is of interest to consider these findings within the context of an even more general developmental achievement, that of infants' developing self-concept. Numerous researchers (i.e., Bahrick & Watson, 1985; Rochat, 1998, 2001b; Rochat & Morgan, 1995; Schmuckler, 1996b; Schmuckler & Fairhall, 2001) have suggested that findings such as these are, at least, an important prerequisite for the development of infants' self-concepts. Within this context, the current findings are even more intriguing in that this work has used less than perfect contingency information, as opposed to the perfect contingencies available in the previous research. It is likely that recognizing and understanding these differences in contingency relations is a powerful basis by which infants learn to differentiate self from other (e.g., Bahrick & Watson, 1985). And in the current study, the contingencies actually provide compelling information for a different, presumably more complex aspect of the self—the idea of the self as a causal agent in the world. Given that such an aspect of the self reflects a more advanced form of self-knowledge, it is not surprising that the young infants in this study may not have understood the intermodal relations underlying such knowledge. Such a conclusion argues strongly for extending investigations of this form of intermodal perception upwards in age. Such research could then potentially shed light not only on infants' intermodal abilities, but also on fundamental aspects of infants' understanding of themselves, and of how the apprehension of various contingency relations might promote more sophisticated self-knowledge.

NOTES

This research was supported by a grant from the Natural Sciences and Engineering Research Council of Canada to Mark A. Schmuckler, and by a predoctoral fellowship awarded to Derryn Jewell from the Natural Sciences and Engineering Research Council of Canada. The authors wish to thank Lorraine Bahrick and an anonymous reviewer for their comments on this manuscript, and Lorraine Bahrick and Philippe Rochat for interesting discussions concerning this line of research in general. Parts of this research were presented at the 13th Biennial Meetings of the International Conference on Infant Studies, Toronto, ON, April 2002.

REFERENCES

Bahrick, L. E. (1988). Intermodal learning in infancy: Learning on the basis of two kinds of invariant relations in audible and visible events. Child Development, 53, 197–209.

Bahrick, L. E. (1994). The development of sensitivity to arbitrary intermodal relations. Ecological Psychology, 6, 111–123.

Bahrick, L. E. (1995). Intermodal origins of self-perception. In P. Rochat (Ed.), The self in infancy: Theory and research (pp. 349–374). Amsterdam: North Holland.

Bahrick, L. E. (2001). Increasing specificity in perceptual development: Infants' detection of nested levels of multimodal stimulation. Journal of Experimental Child Psychology, 79, 253–270.

Bahrick, L. E. (2002). Generalization of learning in three-and-a-half-month-old infants on the basis of amodal relations. Child Development, 73, 667–685.

Bahrick, L. E., Flom, R., & Lickliter, R. (2002). Intersensory redundancy facilitates discrimination of tempo in 3-month-old infants. Developmental Psychobiology, 41, 352–363.

Bahrick, L. E., Hernandez-Reif, M., & Flom, R. (2005). The development of infant learning about specific face-voice relations. Developmental Psychology, 41, 541–552.

Bahrick, L. E., Moss, L., & Fadil, C. (1996). Development of visual self-recognition in infancy. Ecological Psychology, 8, 189–208.

Bahrick, L. E., & Pickens, J. N. (1994). Amodal relations: The basis for intermodal perception and learning in infancy. In D. J. Lewkowicz & R. Lickliter (Eds.), The development of intersensory perception: Comparative perspectives (pp. 205–233). Hillsdale: Lawrence Erlbaum Associates.

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive-visual contingency as a potential basis of self-perception in infancy. Developmental Psychology, 21, 963–973.

Bertenthal, B. I., & Bai, D. L. (1989). Infant's sensitivity to optical flow for controlling posture. Developmental Psychology, 25, 936–945.

Bertenthal, B. I., Rose, J. L., & Bai, D. L. (1997). Perception-action coupling in the development of visual control of posture. Journal of Experimental Psychology: Human Perception and Performance, 23, 1631–1643.

Bhatt, R. S., Wilk, A., Hill, D., & Rovee-Collier, C. (2004). Correlated attributes and categorization in the first half-year of life. Developmental Psychobiology, 44, 103–115.

Bigelow, A. E. (1998). Infants' sensitivity to familiar imperfect contingencies in social interaction. Infant Behavior and Development, 21, 149–162.

Bigelow, A. E. (2001). Discovering self through other: Infants' preference of social contingency. Bulletin of the Menninger Clinic, 65, 335–346.

Bigelow, A. E., & Birch, S. A. J. (1999). The effect of contingency in previous interactions on infants' preference for social contingency. Infant Behavior and Development, 22, 367–382.

Bigelow, A. E., & DeCoste, C. (2003). Sensitivity to social contingency from mothers and strangers in 2-, 4-, and 6-month-old infants. Infancy, 4, 111–140.

Bushnell, E. W., & Boudreau, J. P. (1991). The development of haptic perception during infancy. In M. A. Heller & W. Schiff (Eds.), The psychology of touch (pp. 139–161). Hillsdale, NJ: Erlbaum.

Bushnell, E. W., & Boudreau, J. P. (1993). Motor development and the mind: The potential role of motor abilities as a determinant of aspects of perceptual development. Child Development, 64, 1005–1021.

Catanzaro, A. M., & Schmuckler, M. A. (2002). Response perseveration in barrier crossing. Paper presented at the 13th Biennial International Conference on Infant Studies, Toronto, ON.

de Haan, M., Humphreys, K., & Johnson, M. H. (2002). Developing a brain specialized for face perception: A converging methods approach. Developmental Psychobiology, 40, 200–212.

Field, T. M. (1987). Affective and interactive disturbances in infants. In J. D. Osofsky (Ed.), Handbook of infant development (2nd ed., pp. 972–1005). New York: Wiley.

Flom, R., & Bahrick, L. E. (2001). Is featural information necessary for 5-month-olds' perception of motion specifying the self? Paper presented at the Society for Research in Child Development, Minneapolis, MN.

Gibson, E. J., & Walker, A. S. (1984). Development of knowledge of visual-tactual affordances of substance. Child Development, 55, 453–460.

Gogate, L. J., & Bahrick, L. E. (1998). Intersensory redundancy facilitates learning of arbitrary relations between vowel-sounds and objects in 7-month-olds. Journal of Experimental Child Psychology, 69, 133–149.

Gottfried, A. W., Rose, S. A., & Bridger, W. H. (1977). Cross-modal transfer in human infants. Child Development, 48, 118–123.

Hartshorn, K., & Rovee-Collier, C. (2003). Does infant memory expression reflect age at encoding or age at retrieval. Developmental Psychobiology, 42, 283–291.

Hernandez-Reif, M., & Bahrick, L. E. (2001). The development of visual-tactual perception of objects: Amodal relations provide the basis for learning arbitrary relations. Infancy, 2, 51–72.

Hildreth, K., Sweeney, B., & Rovee-Collier, C. (2003). Differential memory-preserving effects of reminders at 6 months. Journal of Experimental Child Psychology, 84, 41–62.

Jewell, D. T., & Schmuckler, M. A. (2000). Active versus passive movement in infant search. Paper presented at the 12th International Conference on Infant Studies, Brighton, England.

Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns' preferential tracking of face-like stimuli and its subsequent decline. Cognition, 40, 1–19.

Kaye, K. L., & Bower, T. G. R. (1994). Learning and intermodal transfer in newborns. Psychological Science, 5, 286–288.

Kingsnorth, S., & Schmuckler, M. A. (2000). Walking skill versus walking experience as a predictor of barrier crossing in toddlers. Infant Behavior and Development, 23, 331–350.

Legerstee, M., Anderson, D., & Schaffer, A. (1998). Five- and eight-month-old infants recognize their faces and voices as familiar and social stimuli. Child Development, 69, 37–50.

Lewkowicz, D. J. (2000). The development of intersensory temporal perception: An epigenetic systems/limitations view. Psychological Bulletin, 126, 281–308.

Lewkowicz, D. J. (2001). The concept of ecological validity: What are its limitations and is it bad to be invalid. Infancy, 2, 437–450.

Lewkowicz, D. J. & Lickliter R. (Eds.), (1994). The development of intersensory perception: Comparative perspectives. Hillsdale, NJ: Erlbaum.

Lickliter, R., & Bahrick, L. E. (2000). The development of infant intersensory perception: Advantages of a comparative convergent-operations approach. Psychological Bulletin, 126, 260–280.

Lickliter, R., & Bahrick, L. E. (2001). The salience of multimodal sensory stimulation in early development: Implications for the issue of ecological validity. Infancy, 2, 451–467.

Maurer, D., Stager, C. L., & Mondloch, C. J. (1999). Cross-modal transfer of shape is difficult to demonstrate in one-month-olds. Child Development, 70, 1047–1057.

Meltzoff, A. N., & Borton, R. W. (1979). Intermodal matching by human neonates. Nature, 282, 403–404.

Morgan, R., & Rochat, P. (1997). Intermodal calibration of the body in early infancy. Ecological Psychology, 9, 1–23.

Morton, J., & Johnson, M. H. (1991). Conspec and conlern: A two-process theory of infant face recognition. Psychological Review, 98, 164–181.

Muir, D., & Field, J. (1979). Newborn infants orient to sounds. Child Development, 50, 431–436.

Papousek, H., & Papousek, M. (1974). Mirror-image and self recognition in young human infants: I. A new method of experimental analysis. Developmental Psychobiology, 7, 149–157.

Rochat, P. (1998). Self-perception and action in infancy. Experimental Brain Research, 123, 102–109.

Rochat, P. (2001a). The infant's world. Cambridge: Harvard University Press.

Rochat, P. (2001b). Origins of self-concept. In J. G. Bremner & A. Fogel (Eds.), Blackwell handbook of infant development (pp. 191–212). Malden, MA: Blackwell Publishers.

Rochat, P. (2001c). Social contingency detection and infant development. Bulletin of the Menninger Clinic, 65, 347–361.

Rochat, P., & Hespos, S. J. (1997). Differential rooting response by neonates: Evidence for an early sense of self. Early Development and Parenting, 6, 151–158.

Rochat, P., & Morgan, R. (1995). Spatial determinants in the perception of self-produced leg movements in 3- to 5-month-old infants. Developmental Psychology, 31, 626–636.

Rochat, P., & Morgan, R. (1998). Two functional orientations of self-exploration in infancy. British Journal of Developmental Psychology, 16, 139–154.

Rochat, P., & Striano, T. (1999). Emerging self-exploration by 2-month-old infants. Developmental Science, 2, 206–218.

Rochat, P., & Striano, T. (2002). Who's in the mirror? Self-other discrimination in specular images by four- and nine-month-old infants. Child Development, 73, 35–46.

Rose, S. A. (1990). Cross-modal transfer in human infants: What is being transferred? Annals of the New York Academy of Sciences, 608, 38–50.

Rose, S. A., Feldman, J. F., Futterweit, L. R., & Jankowski, J. J. (1998). Continuity in tactual-visual cross-modal transfer: Infancy to 11 years. Developmental Psychology, 34, 435–440.

Rose, S. A., Gottfried, A. W., & Bridger, W. H. (1981a). Cross-modal transfer and information processing by sense of touch in infancy. Developmental Psychology, 17, 90–98.

Rose, S. A., Gottfried, A. W., & Bridger, W. H. (1981b). Cross-modal transfer in 6-month-old infants. Developmental Psychology, 17, 661–669.

Rose, S. A., Gottfried, A. W., & Bridger, W. H. (1983). Infants' cross-modal transfer from solid objects to their graphic representations. Child Development, 54, 686–694.

Rose, S. A., & Ruff, H. A. (1987). Cross-modal abilities in human infants. In J. D. Osofsky (Ed.), Handbook of infant development (2nd ed.). New York: Wiley.

Rovee-Collier, C. K., & Barr, R. (2001). Infant learning and memory. In J. G. Bremner & A. Fogel (Eds.), Blackwell handbook of infant development (pp. 139–168). Malden, MA: Blackwell Publishers.

Rovee-Collier, C. K., & Gekoski, M. J. (1979). The economics of infancy: A review of conjugate reinforcement. In H. W. Reese & L. P. Lipsitt (Eds.), Advances in child development and behavior (Vol. 13, pp. 195–255). New York: Academic Press.

Rovee, C. K., & Rovee, D. T. (1969). Conjugate reinforcement of infant exploratory behavior. Journal of Experimental Child Psychology, 8, 33–39.

Sai, F. Z. (2005). The role of mother's voice in developing mother's face preference: Evidence for intermodal perception at birth. Infant and Child Development, 14, 29–50.

Schmuckler, M. A. (1995). Self-knowledge of body position: Integration of perceptual and action system information. In P. Rochat (Ed.), The self in infancy: Theory and research (pp. 221–241). Amsterdam: Elsevier Science Publishers.

Schmuckler, M. A. (1996a). The development of visually-guided locomotion: Barrier crossing in toddlers. Ecological Psychology, 8, 209–236.

Schmuckler, M. A. (1996b). Visual-proprioceptive intermodal perception in infancy. Infant Behavior and Development, 19, 221–232.

Schmuckler, M. A., & Fairhall, J. L. (2001). Visual-proprioceptive intermodal perception using point light displays. Child Development, 72, 949–962.

Schmuckler, M. A., & Gibson, E. J. (1989). The effect of imposed optical flow on guided locomotion in young walkers. British Journal of Developmental Psychology, 7, 193–206.

Schmuckler, M. A., & Tsang-Tong, H. Y. (2000). The role of visual and body movement information in infant search. Developmental Psychology, 36, 499–510.

Spelke, E. S. (1987). The development of intermodal perception. In P. Salapatek & L. Cohen (Eds.), Handbook of infant perception, Vol. 2: From perception to cognition (pp. 233–273). Orlando, FL: Academic Press.

Stoffregen, T. A., Schmuckler, M. A., & Gibson, E. J. (1987). Use of central and peripheral optical flow in stance and locomotion in young walkers. Perception, 16, 113–119.

Watson, J. S. (1972). Smiling, cooing, and "the game". Merrill-Palmer Quarterly, 18, 323–339.

Watson, J. S. (1979). Perception of contingency as a determinant of social responsiveness. In E. Thoman (Ed.), Origins of the infant's social responsiveness (pp. 33–64). Hillsdale, NJ: Erlbaum.

Watson, J. S. (1985). Contingency perception in early social development. In T. M. Field & N. A. Fox (Eds.), Social perception in infants (pp. 157–176). Norwood, NJ: Ablex.

Watson, J. S. (1994). Detection of the self: The perfect algorithm. In S. T. Parker, R. W. Mitchell, & M. L. Boccia (Eds.), Self-awareness in animals and humans (pp. 131–148). New York: Cambridge University Press.

Watson, J. S. (1997). Contingency and its two indices within conditional probability analysis. Behavior Analyst, 20, 129–140.

Watson, J. S. (2001). Contingency perception and misperception in infancy: Some potential implications for attachment. Bulletin of the Menninger Clinic, 65, 296–320.

Wilk, A., Klein, L., & Rovee-Collier, C. K. (2001). Visual-preference and operant measures of infant memory. Developmental Psychobiology, 39, 301–312.