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Spatial Determinants in the Perception of Self-Produced Leg Movements by 3- to 5-Month-Old Infants

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Sixty 3- and 4–5-month-old infants were simultaneously presented with 2 on-line video images of their own legs. In 3 experiments, the temporal contingency between the 2 images and the infant's actual movements was maintained constant while their spatial relationships were systematically manipulated. In Experiment 1, both spatial orientation and directionality of movement on the visual display were varied. In Experiment 2, only directionality of movement was varied. In Experiment 3, only spatial orientation was varied. Analyses focused on infants' preferential looking and relative amount of leg activity while looking at either view. Results show that both groups of infants actively compared and explored the 2 views of their legs. They looked significantly longer and generated significantly more leg activity while looking at the view displaying a left–right inversion. These results demonstrate that the perception of self-produced leg movements by young infants is partially determined by spatial information about movement directionality. The results are interpreted as evidence of an early detection of intermodal invariants which specify the body as a situated agent in the environment.

Recent progress in infancy research suggests that young infants manifest a preconceptual self, long before the emergence of behavior traditionally associated with self-recognition in front of a mirror (Lewis & Brooks-Gunn, 1979). Young infants have been described as manifesting an early sense of self (Stern, 1985), exploring themselves and behaving as differentiated, coordinated, agentive, and projected entities in the environment (Rochat, 1993). Questions remain as to what kind of information underlies early self-exploration. Meltzoff (1990, 1993) proposed that at the onset of development, infants are sensitive to the spatiotemporal patterns of their own movements, forming the basis of early self-exploration: "there are good theoretical reasons for thinking that the first psychologically primary notion of self concerns not one's featural peculiarities but rather one's movements, body postures, and powers" (Meltzoff, 1990, p. 142). Despite the importance of these questions, few studies have attempted to isolate the perceptual information to which young infants might be sensitive when exploring themselves. Papousek and Papousek (1974) placed 5-month-olds in front of two different video images, either of themselves or of others. Based on the preferential looking of the infant, this method allowed assessment of the discriminant variables between the two video images. Reporting only pilot observations with 11 infants, Papousek and Papousek found that infants preferred to look at images of the self or of others that provide eye contact. Placing 1- to 24-month-old infants in front of two mirrors that were flat, blurred, or distorted, Schulman and Kaplowitz (1976) showed that prior to 6 months, infants tend to look more at the clear than the blurred image of themselves and show less interest in the distorted image than the nondistorted one. These 1- to 6-month-olds spent more time looking at the mirror compared with older infants. However, they did not yet show complex behavior such as looking at a particular body part, followed by an immediate inspection of its reflection.

It has often been suggested that the origins of self-perception correspond to the young infant's discovery of the contingency between visual and proprioceptive feedback from body movements (Guillaume, 1926; Lewis & Brooks-Gunn, 1979; Piaget, 1952; Wallon, 1942/1978). Bahrick and Watson (1985) used the choice method introduced by Papousek and Papousek to study self-exploration for a different part of the body (i.e., the legs). They demonstrated that 5-month-olds are sensitive to proprioceptive–visual contingency. In their experiment, Bahrick and Watson placed the infant in front of two TV monitors, side by side. On one monitor, the infants saw a contingent view of their own legs. The other monitor showed either a noncontingent, prerecorded tape of the baby's own legs or a tape of another baby's leg movements (wearing identical booties). Bahrick and Watson showed that 5-month-olds look preferentially to the noncontingent view. They also observed this phenomenon in a situation in which an occluder prevented the infant from seeing his or her legs directly. In contrast, 3-month-olds showed split preferences. Some looked much longer at the contingent view, and others at the noncontingent one. Overall, Bahrick and Watson demonstrated that early perceptual discrimination of the self-produced movements is not limited to facial images but includes other parts of the body.

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Questions remain as to what information is relevant to young infants' discrimination of intermodal proprioceptive–visual contingency. Bahrick and Watson's (1985) experiment provides only limited information about what is actually detected by the young infant. Is it a temporal contingency, a spatial contingency, or a combination of the two? In other words, does the infants' sensitivity reported by Bahrick and Watson depend only on the *temporal* discrepancy between visual and proprioceptive feedback, or could it also depend on the detection of a change in the spatial calibration of the two sense modalities? In addition, the yoked control design they used only roughly controlled the spatiotemporal contrast between the two images. Specifically, the design used by Bahrick and Watson did not control for specific spatiotemporal aspects contrasting the two images (e.g., movement frequency, duration, or velocity). This inadequate control prevents further interpretation of the exact information used by the infants to discriminate. The present research is an effort to specify the information used by young infants to discriminate *spatial* differences between two images of the self-produced leg movements, their temporal aspect maintained perfectly equal in both. In particular, the question posed here is whether infants detect changes in visual–proprioceptive information specifying two aspects of spatial organization: spatial orientation and directionality of self-produced leg movements. As in the Bahrick and Watson study, the focus is on the period of 3 to 5 months when great progress in the control of action and exploration takes place (Gibson, 1988; Rochat, 1989).

The present research comprises three experiments in which infants were simultaneously presented with two on-line (immediate feedback) images of their legs filmed from different perspectives or with a left–right reversal of the image. The two views of the self were identical with respect to their temporal contingency; only aspects of their spatial organization were varied. In general, the dependent measures were the infants' preferential looking at either one of the images, gaze alternation (amount of visual comparisons between the two images), and the amount of leg activity while looking at either image of the legs as an index of self-exploration.

Experiment 1

Rationale

The question guiding the first experiment was whether infants show discrimination between different perspectives of their own legs. These perspectives were associated with variation in both spatial orientation and directionality of movement, while the temporal contingency in either view was held constant. The rationale was that if infants show discrimination, they would tend to look significantly longer and generate more leg activity while looking at one image over the other. On the basis of the findings of Papousek and Papousek (1974) and Bahrick and Watson (1985), we predicted that in discriminating between the two images of the legs, infants would tend to look longer at the spatially incongruent image, because it conflicts with what is proprioceptively perceived by the infant (i.e., inverted orientation and reversed movement directionality). Furthermore, on the basis of the observations of Bahrick and Watson, we expected a developmental trend in which discrimination would be observed within the group of 4–5-month-olds and not within the group of 3-month-olds.

Method

Sample

Twenty healthy full-term infants (10 girls and 10 boys) were tested. Ten were 3-month-olds (*M* age = 3 months 13 days; range = 3 months 1 day to 3 months 28 days; *SD* = 10 days), and 10 were 4–5-month-olds (*M* age = 4 months 18 days; range = 4 months 3 days to 5 months 14 days; *SD* = 15 days). The infants were recruited from a subject pool consisting of over 500 infants born in the Atlanta area. Parents were contacted by phone and were invited to participate with their infant. Overall, a total of 26 infants were tested. Of the 6 who were not included in the final sample, 3 cried, and 3 looked less than 15% of the test period at the TV.

Procedure and Apparatus

We presented to both groups of infants two different perspectives of their own legs from the waist down on a split screen of a large 25-in. video monitor (Panasonic CT25824). The infants were seated in a 60° reclined infant seat looking up toward the TV, which was inclined 30° at a distance of 2 m from the infant's eyes (see Figure 1).

The reclined posture of the infants prevented them from seeing their own legs directly, unless they lifted up their head and looked down. One camera (Panasonic black-and-white CCTV HWV-BL294) was placed 1 m away, in front of the infant, to provide a frontal view of the infant's legs from the waist down. This first view of the infant's legs (the observer's view) was projected to one side of the split screen with a Pelco video splitter (Pelco US100DT), generating a split image along the middle vertical axis of the television screen. An identical camera was placed 1 m above the infant to provide a view of the infant's legs equivalent to the one he or she would normally perceive when looking down directly toward them. This second perspective of the infant's legs (the ego view) was projected to the other side of the split screen. Both images were carefully controlled for identical contrast and size, hence amount of motion, before and during each testing session. The temporal aspect of the contingency was absolutely the same in both views of the infant, because both views were synchronous with the infant's own behavior. As illustrated in Figure 2A, the two views (observer's and ego) only differed in spatial orientation and movement directionality.

The side of the screen on which the observer's view occurred was counterbalanced between the two groups of infants. Five of the infants in each group saw the observer's view on the left of the split screen, and 5 saw it on the right. To entice the infant to look at the TV, we put long socks with black-and-white stripes on the baby's feet and legs (see Figure 2). Furthermore, to encourage them to move their legs, thus providing some potentially interesting action on the screen, we placed a small tie pin microphone (Realistic 33-1063) under the infant's feet on the lower part of the seat, taped to the underside of a sheet of paper, under a white cotton cloth on which the feet rested. The sheet of paper acted to spread out the sounds that the infants made while kicking their feet above the area over the microphone. The microphone, invisible to the infant, was connected to a miniamplified speaker system (Realistic 32-2040, 16.5 × 12.5 cm) affixed on top of the TV. Contingent to any leg movement, this device produced a commensurate rustling and scratching sound originating from the speaker on top of the TV monitor. This auditory feedback provided the infant with contingent sound accompanying the legs' movements. Such contingent sound enticed the infant to generate movements and to orient toward the location of the sound (the video monitor). A third Panasonic S-VHS movie camera (AG-450 with a 10× power zoom lens with autofocus) placed about

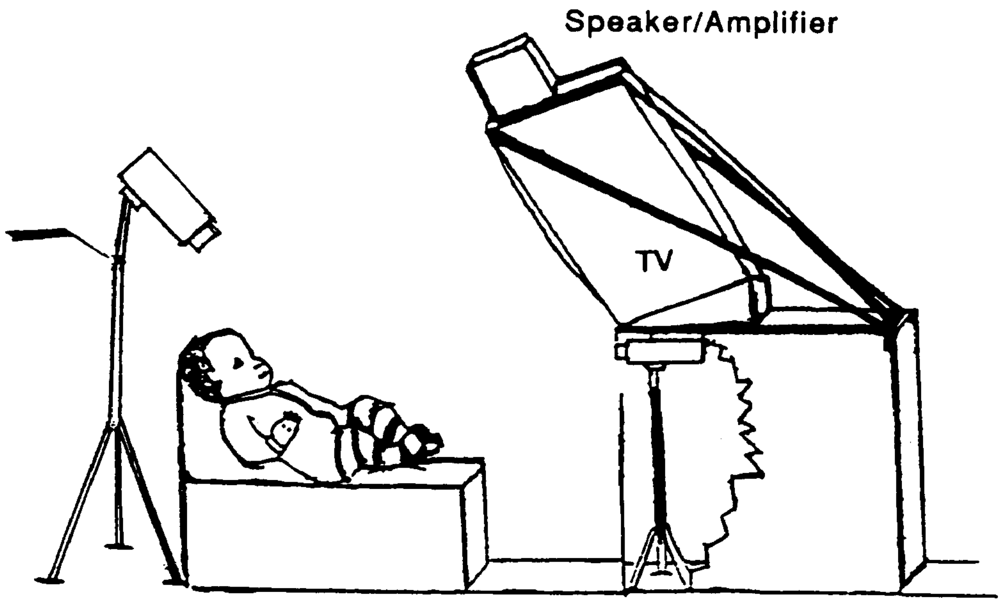

Figure 1. The apparatus as it was set up for Experiments 1 and 3.

2 m in front of the infant's face provided a close-up video recording of the infant's eyes. The video and audio recording of this camera was used for further analyses of both the infant's preferential looking and the amount of leg activity while gazing at either view of the self. This third camera was placed under the table that supported the TV monitor (see Figure 1). Except for the lenses emerging from holes in a black Foamcore sheet used as a backdrop, the cameras facing the infant were out of his or her view. The two views of the infants' legs were recorded by a video cassette recorder (Panasonic AG-1270) as it appeared to the infant throughout the 5-min test.

Parents watched their infant during testing from an adjacent room through a one-way mirror. After the infant was secured and comfortably seated in front of the TV monitor, a preliminary calibration of the infant's relative gaze to various portions of the screen was performed and videotaped by Camera 3. In the calibration phase, we shook a rattle in front of the monitor to the right of the screen, to the middle of the screen, to the left of the screen, and back to the middle again. From the video recording of the infant's gazing during this calibration phase, coders were able to gauge for each individual infant the relative difference between a look to the left and a look to the right of the screen. This calibration lasted about 15 s during which a colorful curtain with a Mickey Mouse print covered the TV screen.

The test phase started immediately after calibration and lasted 5 min, during which the infant was able to freely explore the two views of his or her legs. The testing session started when the curtain covering the TV was lifted. The two views of the infant's own legs were revealed, and the microphone placed below the legs was turned on. During the whole testing session, one experimenter stood directly behind the infant, invisible to the infant who was facing the TV monitor. This experimenter monitored the test and checked for any changes in the quality of the two views during the 5 continuous minutes of the testing session. Another experimenter, also invisible to the infant, kneeled under the table by the video equipment, behind the Foamcore sheet used as a backdrop. Her task was to time the testing session, checking on the cameras and the video recording. At the end of the 5-min testing session, the curtain was put back over the TV monitor and the baby was picked up from the seat.

Scoring and Dependent Measures

The audio and video recordings of the camera providing the close-up of the infant's face were scored for (a) looking at either the right or the left view on the TV screen and (b) contingent leg activity produced by the infant.

Looking. Two independent coders coded gazing behavior at either view of the self using a computerized event recorder with multiple input channels running on the computer's clock. Two channels (1 and 2) were used to score infants' looking. These two channels were controlled by predetermined keys on the computer's keyboard, one corresponding to looking to the right of the TV monitor, the other to the left.

Leg activity. While a coder made the pass through the video recording to code the infants' looking, the audio recording of the sound generated by the infant's leg movements via the microphone placed under his or her feet was simultaneously digitized by a Ceder Sound Digitizer (CSD from Ceder Technology, Phoenix, AZ) and imported into the computer on another channel of the event recorder. The digitized sound corresponding to leg movements of the infant was recorded initially as a sound spectrogram (volume over time). At the end of the coding, a program performed a post hoc transformation of the imported sound spectrogram into successive periods of activity or no activity of the legs. This transformation used another channel of the event recorder on which looking activity was simultaneously coded. This transformation was based on a set threshold corresponding to one third of the maximum input recorded on the sound spectrogram. When the sound picked up exceeded the one-third threshold, the program transformed a threshold crossing as an episode of leg activity of 2 s in duration, recorded on the channel of the event recorder. On the basis of pilot observations, the unit of 2 s was chosen to approximate the characteristics of a typical bout of the infants' leg movements. Events entered on one channel of the event recorder corresponded to the infant looking to the right portion of the split screen, and on a second channel, looking to the left. Note that the events entered on these two channels were mutually exclusive. When no events were coded on either the first or second channel, the infant was looking away from the TV screen. Simultaneously, the threshold episodes of leg activity (based on the transformation of the sound spectrogram described earlier) were recorded on a third channel.

Based on the simultaneous records entered on all three channels of the event recorder, a program calculated the relative duration in seconds of (a) looking at the left or right side of the TV monitor, (b) leg activity, and (c) co-occurrence of leg activity and looking at either side of the TV

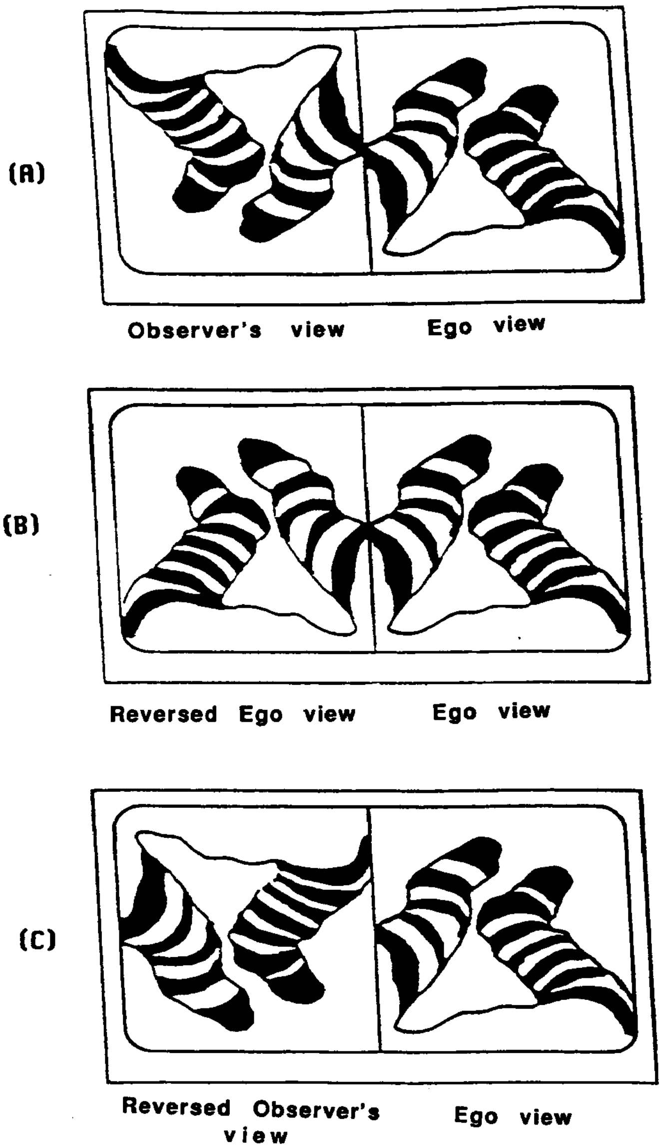

Figure 2. The two views of their own legs as seen by the infants on the TV display in Experiment 1 (A), Experiment 2 (B), and Experiment 3 (C).

monitor. The co-occurrence was calculated in terms of overall duration of leg movement as a percentage of the total time spent looking at a particular view, [(leg activity while looking at a particular view)/(looking at this particular view) × 100]. Finally, on the basis of the event recorder transcript and as an index of visual comparison between the two views of the legs, coders measured (d) the frequency of gaze alternation from one side of the screen to the other, when the switching of gaze orientation occurred within a 1-s interval.

For all measures pertaining to visual behavior, within- and between-coders reliability tests performed on one third of the infants yielded Pearson's correlations greater than .92.

Results

Looking

As shown in Table 1, both groups of infants spent more time looking at the TV monitor than looking away. Table 1 also shows that, while looking at the TV, infants spent more time gazing at the observer's view, compared with the ego view. Analysis of the number of seconds spent looking at either view of the legs confirms this general pattern. However, this pattern is dependent on the infants' age. Contrary to what was expected, the pattern is more accentuated by 3-month-olds, although a similar trend is found with the group of 4–5-month-olds. A 2 (age) × 5 (minute) × 2 (view) mixed-design analysis of variance (ANOVA; with age as a between-subjects variable and minute and view as within-subjects variables) performed on looking duration in seconds yielded a significant Age × View interaction only, $F(1, 18) = 6.855$, $p < .02$. Post hoc Tukey tests show that the effect of view is significant for the 3-month-olds ($p < .01$) and marginally significant for the 4–5-month-olds ($p < .06$). In addition, a 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA on the percentage (see Table 1) of time looking at either view over the 5-min test presentation yielded a significant main effect of view only, $F(1, 18) = 34.953$, $p < .0001$. This pattern is robust and is further supported by the fact that for both age groups, 9 out of the 10 infants spent more time looking at the observer's view of their legs compared with the ego view ($p < .02$, binomial test).

Finally, to assess whether the pattern of preference for the observer's view over the ego view could be caused by an anchoring of the infant's gaze to one particular view, we further analyzed looking behavior in terms of the frequency of gaze switching from one view to the other, minute by minute over the 5-min test presentation. A 2 (age) × 5 (minute) mixed-design ANOVA performed on the frequency of gaze switching yielded a significant main effect of minute, $F(4, 72) = 7.831$, $p < .0001$. This significant minute effect corresponds to a general decline in the frequency of switching at both ages (average frequency of 14 switches in the first minute, 12 in the second, 10 in the third, 7 in the fourth, and 6 in the fifth minute). This result suggests that the pattern of preferential looking was based on a comparison of the two views and an active exploration of their spatial differences. The extensive amount of switching that was demonstrated by the infant is inconsistent with the possibility of an anchoring of the gaze to one particular view (i.e., the observer's view).

In summary, the analysis of looking indicates that (a) there is a significant pattern of preference for the observer's view, (b) this pattern is particularly marked in the younger group of infants, and (c) this pattern is based on a process of comparison between the two views of the self.

Leg Activity

On average, both groups of infants had significantly more leg activity while looking at the TV, compared with looking away (see Table 1). A 2 (age) × 2 (gaze direction) ANOVA yielded a significant effect of gaze direction only, $F(1, 18) = 64.937$, $p < .0001$. This demonstrates that infants actively responded to the visual–proprioceptive contingency of the display. Leg activity while looking at the TV was further analyzed as a percentage of the time spent looking at either the ego or the observer's view, [(leg activity while looking at a particular view)/(looking at this particular view) × 100]. Results show that infants tended to generate proportionally more leg activity while looking at the

Table 1
Means and Standard Deviations for Looking Durations, Proportion of Looking, and Leg Activity for Both Groups of Infants in Experiment 1

Age	Looking (in s)				Looking (%)			Leg activity (%)			
	Away from TV	At TV	Observer's view	Ego view	At TV	Observer's view	Ego view	Away from TV	At TV	Observer's view	Ego view
3 months											
M	64	236	179	58	79	76	24	3	25	26	18
SD	34	34	45	42	11	19	18	2	12	11	15
4–5 months											
M	146	154	100	58	51	65	35	13	35	36	32
SD	42	43	35	33	14	23	21	8	15	18	14

Note. Because of rounding error, the combined looking times to the observer's and ego views are slightly greater than the total looking time at the TV. This error comes from the cumulative reaction time during on-line coding on the event recorder.

observer's view compared with the ego view. A 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA yielded a significant main effect of minute, $F(4, 72) = 2.598, p < .03$, and a marginally significant main effect of view, $F(1, 18) = 4.11, p < .057$, with no significant interactions. Analysis of the simple effects showed that as a function of minute, percentage of leg activity while looking at the TV increased significantly between the second and third minute of testing.

In summary, the analysis of leg activity indicates that (a) infants of both age groups learn about the visual-proprioceptive contingency of the display, (b) infants' leg activity, while infants were looking at the TV, increases as a function of minute of testing, and (c) infants tend to generate more leg movements while looking at the observer's (i.e., incongruent) view compared with the ego (i.e., congruent) view of their legs.

Discussion

In general, the results of this first experiment demonstrate that from 3 months of age, infants show discrimination of different perspectives of their legs. They tend to look significantly longer at the observer's view of their own legs compared with the ego view. This result confirms the general pattern of preferential looking toward the incongruent view reported by Papousek and Papousek (1974) and Bahrick and Watson (1985), who used a similar preferential looking paradigm. If we assume that the observer's view is novel to the infant, the results express infants' active engagement in exploring the novelty of this view. This exploration is further supported by the fact that the pattern of preferential looking settled by the second half of the test presentation, after an active comparison between the two views had taken place. Within the perspective of development, the pattern of preferential looking toward the observer's view was significantly more accentuated for the younger group of infants. Contrary to what was expected, 3-month-olds manifested more sensitivity to the different views of their legs compared with 4–5-month-olds.

To further specify the results obtained in Experiment 1, we designed Experiment 2 to unconfound the differences between the two views of the legs and eventually account for the unexpected age difference. In Experiment 1, the observer's view differed from the ego view along two dimensions that were confounded: the inverted orientation (up–down) of the legs and the reversed (left–right) directionality of the legs in relation to the horizontal plane of the monitor's display (see Figure 2A). In Experiment 2 (see Figure 2B), the orientation of the two images was unconfounded by presenting the infants with two ego views of their legs (identical spatial orientation). However, one of the images maintained a left–right reversal (reversed directionality of movements). Recall that in Experiment 1, this left–right directionality reversal was only present in the observer's view.

Experiment 2

Rationale

The second experiment was designed to further specify young infants' sensitivity to spatial differences between two video images of their own legs, and in particular differences in the directionality of self-produced leg movements. The question guiding the study is whether infants show discrimination between two identical perspectives of their legs (both ego views), one displaying a left–right reversal. Using a preferential looking paradigm, we presented infants with two on-line video images of their legs from the waist down from an ego view perspective (see Figure 2B). These two images varied in the directionality of movement while keeping both their temporal contingency and spatial orientation constant. The rationale was that if infants show discrimination, they would tend to look significantly longer and generate more leg activity while looking at one image over the other. As a working hypothesis, and on the basis of the pattern observed in the first experiment, infants of both age groups were expected to look longer at the image displaying a reversed directionality of self-produced movements. They were also expected to generate significantly more leg activity while looking at the reversed ego view, because this view conflicts with regular spatial calibration between vision and proprioception.

Method

Sample

Twenty healthy full-term infants (6 girls and 16 boys) were divided into two groups. Ten were 3-month-olds (*M* age = 3 months 13 days;

range = 3 months 2 days to 3 months 29 days; SD = 9 days), and 10 were 4–5-month-olds (M age = 4 months 15 days; range = 4 months 0 days to 5 months 8 days; SD = 12 days). The infants were recruited from a subject pool consisting of over 500 infants born in the Atlanta area. Parents were contacted by phone and were invited to participate with their infant. Overall, a total of 25 infants were tested. Of the 5 not included in the final sample, 3 cried and 2 looked at the TV less than 15% of the test period.

Procedure and Design

The same basic paradigm, procedure, design, data collection, and analysis described for Experiment 1 was used in this second experiment. Two cameras provided the infant with an ego view of his or her legs from the waist down. These cameras were placed side by side, behind the infant, oriented down toward their legs from above his or her head (1 m away from the infant's legs). One of the two cameras was modified to provide a left–right reversal of the image displayed on the TV monitor. This camera was a tube camera (Panasonic CCTV Model WV-1410) with a horizontal scan reversal modification. This modification was accomplished by having the camera scan the face of the vidicon tube's light-sensitive material in reverse of the direction it normally does. The beam that normally scans the tube face from left to right was modified to scan it from right to left, ultimately revealing a left–right image reversal.

In short, the display provided the infant with two ego views of the legs from the waist down. In one view, the directionality of movement was congruent with the infant's own movements to either the right or to the left. That is, when the infant moved his or her legs to either the right or the left, the legs on the TV monitor moved in the corresponding direction. In contrast, the other view presented to the infant was identical but reversed. In this view, when the infant moved to the right, the image on the screen moved to the left, and vice versa. This modification was the only difference between the two views. As in Experiment 1, the side of either view of the legs presented on the left or right of the split screen was counterbalanced among the infants of each age group.

For all measures pertaining to visual behavior, within- and between-coders reliability tests performed on one third of the infants yielded Pearson's correlations greater than .92.

Results

Looking

During the 5 min of test presentation, both groups of infants spent more time looking at the TV monitor than looking away (see Table 2). Analysis of the number of seconds spent looking at either view of the self shows a general pattern of preference for the reversed ego view over the ego view (see Table 2). A 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA performed on looking duration in seconds yielded a significant main effect of view only, $F(1, 18) = 5.137$, $p < .04$. In addition, a 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA on the percentage of time looking (see Table 2) at either view over the 5-min test presentation yielded a significant main effect of view only, $F(1, 18) = 5.394$, $p < .03$. This result confirms that at both ages, infants' preferential looking toward the reversed ego view of their legs is above chance. This pattern is further supported by the fact that for both age groups, 8 out of the 10 infants spent more time looking at the reversed ego view of their legs compared with the ego view ($p < .06$, binomial test).

As in Experiment 1, to assess whether the pattern of preference for the reversed ego view could be merely caused by an anchoring or stable fixation of the infant's gaze to one particular view, we further analyzed looking behavior. Specifically, the frequency of gaze switching from one view to the other was analyzed minute by minute over the 5-min test presentation. This analysis revealed that for both groups, the pattern of preferential looking was based on a comparison of the two views and an active exploration of their spatial differences. Average frequency of gaze switching was 7.38 for the 3-month-olds and 12.54 for the 4–5-month-olds. Again, the extensive amount of switching is inconsistent with the possibility of an anchoring of the gaze to one particular view (i.e., the reversed ego view). Switching of gaze from one view to the other appeared to decrease progressively as a function of minute, only for the group of 4–5-month-olds. A 2 (age) × 5 (minute) mixed-design ANOVA performed on the frequency of gaze switching yielded a significant Age × Minute interaction, $F(4, 72) = 2.65$, $p < .04$. Analysis of the simple effects revealed a significant effect of minute for the 4–5-month-olds only ($p < .03$). This effect corresponds to a progressive decrease in the frequency of switching, from 15 switches during the first minute to 8 by the fifth minute of the test presentation. Three-month-olds' frequency of switching behavior did not decrease over the course of the 5-min test.

In summary, the analysis of looking indicates that (a) there is a significant pattern of preference for the reversed ego view, (b) this pattern is similar for both age groups, and (c) this pattern is based on a process of comparison between the two views of the legs.

Leg Activity

On average, both groups of infants showed more leg activity when looking at the TV monitor, compared with looking away (see Table 2). A 2 (age) × 2 (gaze direction) ANOVA yielded a significant effect of gaze direction only, $F(1, 18) = 36.036$, $p < .0001$. This suggests that they actively responded to the visual–proprioceptive contingency of the display. Leg activity while looking at the TV was further analyzed as a percentage of the time spent looking at either the ego or the reversed ego view, [(leg activity while looking at a particular view)/(looking at this particular view) × 100]. A 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA yielded a significant main effect of minute, $F(4, 72) = 4.131$, $p < .005$, and a significant main effect of view, $F(1, 18) = 5.878$, $p < .03$. The significant effect of minute corresponds to an increase of overall leg activity over time. The significant effect of view corresponds to the fact that infants tended to generate proportionally more leg activity while looking at the reversed ego view compared with the ego view (see Table 2).

In summary, the analysis of leg activity indicates that (a) infants of both age groups learn progressively about the visual–proprioceptive contingency of the display, (b) this learning is expressed in terms of a progressive and significant increase in leg activity while looking at the TV over the 5-min test presentation, and (c) infants generate significantly more leg movements while looking at the reversed ego (i.e., incongruent) view compared with the ego (i.e., congruent) view of their legs.

Discussion

This second experiment demonstrates that from 3 months of age infants are sensitive to differences in the directionality of

Table 2
Means and Standard Deviations for Looking Durations, Proportion of Looking, and Leg Activity for Both Groups of Infants in Experiment 2

	Looking (in s)				Looking (%)			Leg Activity (%)			
Age	Away from TV	At TV	Reversed ego view	Ego view	At TV	Reversed ego view	Ego view	Away from TV	At TV	Reversed ego view	Ego view
3 months											
M	103	197	115	82	67	58	42	5	24	25	22
SD	58	58	55	34	19	28	17	4	17	17	15
4–5 months											
M	94	206	122	84	69	59	41	7	26	31	17
SD	58	51	46	44	17	22	21	6	16	18	14

self-produced movements of their legs. Analysis of preferential looking indicates that infants discriminate between two identical perspectives of their legs, one displaying a left–right reversal. Infants show a significant preference for the view of their legs with identical temporal contingency and spatial orientation but reversed directionality of movement. Remember that in Experiment 1 the two images on display were temporally contingent (on-line views of the legs), varying both in spatial orientation and directionality of movement (see Figure 2A). The aim of this second experiment was to untangle spatial orientation and directionality of movement as spatial determinants of the infant's preferential looking. Results show that a change in directionality only (left–right reversal) is sufficient to replicate the pattern of preferential looking discovered in Experiment 1. This result suggests that infants detect the incongruence of an image of their legs that displays the same spatial orientation but a reversal in the direction of movement. As in Experiment 1, the results show that at both ages infants are actively engaged in exploring the view that violates the regular calibration of visual and proprioceptive space. In general, infants generate significantly more leg activity while looking at the TV, and in particular while looking at the incongruent (reversed ego) compared with the congruent (ego) view of their legs.

Experiment 2 replicates the pattern of preferential looking found in the first experiment, based only on a reversal of one of the views of the legs. This result does not negate the possibility that spatial orientation did play a role in determining the pattern of preferential looking observed in Experiment 1. On the basis of the data collected so far, change in the directionality of movement is sufficient but may or may not be necessary in determining the pattern of preferential looking observed in Experiment 1. The aim of the third and last experiment is to see whether a change in spatial orientation alone could also be sufficient in determining this pattern of preferential looking and apparent discrimination.

Experiment 3

Rationale

The question guiding this experiment was whether infants show discrimination between different perspectives of their legs (ego view and observer's view) when these perspectives correspond to the same directionality of movement but different spatial orientations. Infants were presented with two on-line video images of their legs from the waist down and, as in Experiment 1, one image corresponded to an ego view and the other to an observer's view. To maintain a congruent and identical directionality of movement in both views, the observer's view displayed a left–right reversal (see Figure 2C). These two images varied in spatial orientation only while keeping the directionality of movement and their temporal contingency constant. The rationale was that if infants are sensitive to and show discrimination of the spatial orientation of their legs, they would tend to look significantly longer and generate more leg activity while looking at one image over the other. In particular, they would look longer and generate more leg activity while looking at the observer's view, because this view is the least congruent compared with the ego view, which corresponds to what infants experience while exploring their own legs directly.

Method

Sample

Twenty healthy full-term infants (10 girls and 10 boys) were divided into two groups. Ten were 3-month-olds (*M* age = 3 months 15 days; range = 3 months 2 days to 3 months 25 days; *SD* = 9 days), and 10 were 4–5-month-olds (*M* age = 4 months 27 days; range = 4 months 0 days to 5 months 12 days; *SD* = 12 days). The infants were recruited from a subject pool consisting of over 500 infants born in the Atlanta area. Parents were contacted by phone and were invited to participate with their infant. Overall, a total of 29 infants were tested. Of the 9 not included in the final sample, 1 fell asleep, 2 cried, and 6 looked at the TV less than 15% of the test period.

Procedure and Design

The same basic paradigm, procedure, design, data collection, and analysis described for Experiment 1 was used in this third experiment. Two cameras provided the infant with an ego view and an observer's view of his or her legs from the waist down. These cameras were placed, one in front of the infant (reversed observer's view) and one behind the infant (ego view), both oriented down toward his or her legs. The camera providing the reversed observer's view was modified to provide a left–right reversal of the image displayed on the TV monitor (the modified camera used in Experiment 2).

The display provided the infant with two views of his or her legs from the waist down. In both views, the directionality of movement was congruent with the infant's own movements. That is, when the infant moved his or her legs to either the right or the left, the legs on both images presented on the TV monitor moved in the corresponding direction. The only difference between the two views was the inverted spatial orientation of the legs (see Figure 2C). In the observer's view, the feet were pointing down, toward the lower part of the TV screen. In the ego view, they were pointing up, toward the upper part of the screen. Again, the side presentation of either view of the legs, on the left or right side of the split screen, was counterbalanced among the infants of each age group.

For all measures pertaining to visual behavior, within- and between-coders reliability tests performed on one third of the infants yielded Pearson's correlations greater than .92.

Results

Looking

On average, both groups of infants spent more time looking at the TV monitor, compared with looking away (see Table 3). Analysis of the number of seconds spent looking at either view of the self indicates that, for both age groups, there is no significant preference for either view. The results are shown in Table 3. A 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA performed on looking duration in seconds yielded no significant effect of view, $F(1, 18) = 1.548$, $p < .23$, nor any significant minute or age effect. In addition, a 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA on the percentage of time looking at either view over the 5-min test presentation (see Table 3) yielded no significant main effect of view, $F(1, 18) = 1.56$, $p < .23$, and again no significant age or minute effect. This result confirms that at both ages, there is no preference in looking at either view. Of 10 of the 3-month-olds, 6 showed proportionally more looking at the ego view, and 4 showed more looking at the reversed observer's view. Of 10 of the 4–5-month-olds, 4 preferred the ego view, and 6 preferred the reversed observer's view.

As in the other experiments, looking behavior was further analyzed in terms of the frequency of gaze switching. Switching frequency was analyzed minute by minute over the 5-min test presentation. A 2 (age) × 5 (minute) mixed-design ANOVA performed on the frequency of gaze switching yielded a marginally significant effect of minute only, $F(4, 72) = 2.391$, $p < .06$, and no significant Age × Minute interaction. As in the other two experiments, switching of gaze from one view to the other tended to progressively decrease as a function minute (i.e., from 10 in the first minute to 7 in the fifth). Again, the extensive amount of switching is inconsistent with the possibility of an anchoring of the gaze to one particular view.

In summary, the analysis of looking indicates that (a) there is no preference for either the reversed observer's view or the ego view, (b) this pattern of results applies to both age groups, and (c) although there is no preference for either view, infants appear actively engaged in comparing the two views.

Leg Activity

On average, both groups of infants showed more leg activity while they were looking at the TV monitor compared with looking away (see Table 3). A 2 (age) × 2 (gaze direction) ANOVA yielded a significant effect of gaze direction only, $F(1, 18) = 29.389$, $p < .0001$. This suggests that they actively responded to the visual–proprioceptive contingency of the display. Leg activity while looking at the TV was further analyzed as a percentage of the time spent looking at either the ego or the reversed observer's view, [(leg activity while looking at a particular view)/(looking at this particular view) × 100]. Table 3 shows that infants tend to generate proportionally the same amount of leg activity while looking at the reversed observer's view as compared with the ego view. A 2 (age) × 5 (minute) × 2 (view) mixed-design ANOVA yielded no significant main effect of minute, $F(4, 72) = 1.939$, $p < .113$, and no significant main effect of view, $F(1, 18) = 0.109$, $p < .745$.

In summary, the analysis of leg activity indicates that (a) infants of both age groups become attuned to the visual–proprioceptive contingency of the display, but (b) infants do not show a progressive increase of leg activity as a function of testing time, and (c) infants do not generate more leg activity while looking at either view.

Discussion

This third experiment demonstrates that infants at both ages showed no significant preference for either the reversed observer's view or the ego view. In this experiment, the directionality of movement in both views presented on the TV monitor was congruent with the infant's own movements. The results of this experiment indicate that infants do not show a preference between the two spatial orientations of their legs. In relation to Experiment 1 and 2, these results clearly demonstrate that directionality of movement is the information underlying infants' preference. Recall that in Experiment 1 (see Figure 2A), the two images displayed were temporally contingent (on-line views of the legs) but varied both in spatial orientation and directionality of movement. In Experiment 2, the views were temporally contingent but varied in directionality and not in spatial orientation. The aim of this third experiment was to further untangle spatial orientation and directionality of movement as spatial determinants of the infant's preferential looking, by only varying spatial orientation (see Figure 2C). Results show that a change in spatial orientation (i.e., change in camera perspective with no left-to-right reversal) negates the preference found in Experiments 1 and 2. In this third experiment, infants did not manifest a preference for either view of their legs based on differences in spatial orientation. As in Experiments 1 and 2, results show that at both ages, infants were actively engaged in exploring the display. The visual–proprioceptive experience of the display, combined with the contingent sound picked up by the microphone, caused infants to generate significantly more leg activity while looking at the TV. Note that for this last experiment, the attrition rate of infants who looked less than 15% of the test period is twice as great compared with those of Experiments 1 and 2. This greater attrition rate could possibly be caused by the nature of the visual display or the particular subject sample.

Overall, these results demonstrate that in the first two experiments, directionality of movement was the crucial variable capturing the infants' attention and causing their preference.

General Discussion

Previous research has shown that the perceptual discrimination of self-produced limb movements in early infancy depends

Table 3
Means and Standard Deviations for Looking Durations, Proportion of Looking and Leg Activity for Both Groups of Infants in Experiment 3

Age	Looking (in s)				Looking (%)			Leg Activity (%)			
	Away from TV	At TV	Reversed observer's view	Ego view	At TV	Reversed observer's view	Ego view	Away from TV	At TV	Reversed observer's view	Ego view
3 months											
M	82	218	95	124	73	44	56	5	18	18	18
SD	59	59	78	75	20	36	34	4	12	11	11
4–5 months											
M	175	125	47	78	42	37	63	7	25	22	29
SD	78	78	26	65	26	21	52	6	9	13	10

on the temporal contingency between proprioceptive and visual feedback (Bahrick & Watson, 1985; Papousek & Papousek, 1974). These results demonstrate that infants from 5 months of age detect changes and discrepancies in temporal contingency. In addition, the present research demonstrates that aside from temporal contingency, the perception and discrimination of self-produced leg movements in infants as young as 3 months of age is based on particular aspects of spatial congruity and organization. In an experimental context in which temporal contingency was maintained constant, infants are shown to detect discrepancies in the directionality of self-produced leg movements caused by a left–right inversion. The directionality of movement and its relative congruence with what is regularly experienced by the infant is shown to be an important determinant of early self-exploration. Furthermore, our research shows that the directionality of movement determines the exploration of self-produced leg movements independently of the spatial orientation of the visible body part. Results of Experiment 1 indicate that infants discriminate between two views of self-produced leg movements varying both in spatial orientation and directionality. Results of Experiment 2 demonstrate that when spatial orientation is maintained constant, changes in movement's directionality are discriminated by the infants. Finally, results of Experiment 3 further demonstrate that the spatial determinant of infants' self-exploration and discrimination is the directionality of movement and not the spatial orientation. In the third experiment in which the spatial orientation of the image was inverted but the directionality of movement was congruent with the regular calibration of proprioceptive–visual space, infants showed no signs of discrimination.

The salience of movement's directionality as a determinant of early self-exploration corroborates recent findings revealing precocious cognitive and perceptual competencies only when infants are presented with dynamic displays. The work of Spelke and collaborators show that the physical continuity of a partly occluded object, or the persistence of an object momentarily out of sight, is first perceived and understood in relation to motion (Spelke, 1985). It is not before the end of the first year that infants start perceiving these characteristics based on Gestalt principles (i.e., good continuation) or manifest such physical knowledge in reference to static objects. Young infants are primarily sensitive to motion information than to Gestalt features or differences in appearance such as spatial orientation. As in the case of object perception, the data and basic phenomenon reported here indicate that early in development, self-exploration is primarily based on information arising from movement.

In addition to temporal determinants, there are spatial determinants to the perception of self-produced leg movements in early infancy. Infants are sensitive to the temporal contingencies as well as the spatial congruence between the proprioceptive and visual feedback from self-generated limb movements. With respect to spatial congruity, infants are sensitive to the spatial discrepancy between an image that corresponds to what they experience while looking directly at their own moving limbs and an image that reverses some of its spatial invariants. In detecting these discrepancies, infants demonstrate that they are attuned to intermodal invariants that underlie the calibration of visual and proprioceptive space. This attunment is evident in all three measures of preferential looking, visual comparison, and leg activity displayed by the infants. In general, infants are shown to explore the spatially incongruent view of their legs and to compare it with the congruent view that corroborates the regular calibration of intermodal space. In Experiments 1 and 2, the analyses of looking behavior show that at both ages, infants are engaged in comparing the two views, demonstrating frequent gaze alternations that become significantly less frequent as a function of testing time. Furthermore, the analyses of the frequency of leg movements show that infants tend to be more active while looking at the incongruent view than at the congruent one. In Experiment 2 in which the spatial orientation was identical, the detection of differences between the two views depended exclusively on self-generated leg movements. Analysis of these movements demonstrates that infants of both age groups were actively involved in exploring the differences between the visual–proprioceptive invariants associated with each view, preferring the peculiarities of the incongruent one.

Based on the results reported by Bahrick and Watson (1985), temporal determinants of self-exploration appear to be clearly evident by 5 months. In contrast, the present research provides evidence that by 3 months, self-exploration also depends on the spatial organization of the directionality of movement. These results suggest that spatial determinants may precede temporal ones in the development of self-exploration in infancy. However, this interpretation needs further empirical support as the experimental paradigm used in the present research was a modified version of the one used by Bahrick and Watson. Specifically, in the present research, each leg movement produced a commensurate, compelling sound. This contingent sound clearly enhanced the infants' engagement and might explain the age difference in the findings of the two studies, independently of the spatial or temporal factors that were manipulated in both studies.

In all the experiments reported here, for both age groups, the same general pattern of discrimination is observed. Nevertheless, two age differences were found regarding the magnitude of the general trends. First, in Experiment 1, 3-month-olds manifest a stronger preference for the observer's view, compared with the group of 4–5-month-olds. This result was unexpected. Because it was not replicated in Experiment 2, it might be due to the sample of infants tested in the first experiment. Future research confirming this finding is warranted before further interpretation. Second, analysis of visual exploration as a function of testing time shows that younger infants demonstrated a significantly slower decline (Experiment 1) or no decline at all (Experiment 2) in the frequency of gaze alternations between the two views. These results indicate that compared with the older group, 3-month-olds take more time to settle into a preference for the incongruent view. This could mean that the younger infants are slower in analyzing and processing the differences between the two views of the legs on the display. Given that the same general patterns of preferential looking are observed at both ages in all three experiments, it is probable that infants attended to the same contrasted elements of the two views, but on a different time frame depending on their age.

At a more speculative level of analysis, it is possible to view the present results as informative about the nature of self-exploration by young infants, long before they show self-recognition in front of a mirror. Young infants appear to be attuned to certain aspects of invariant perceptual information (directionality of movement) used to calibrate intermodal space. Without such attunment, infants would not show the phenomenon reported here, in particular the discrimination of an incongruent visual–proprioceptive experience. The detection of an inversion in the directionality of self-produced leg movement presupposes that infants perceive changes in the spatial regularities associated with the vision and proprioception of their own legs in motion. From 3-months of age, infants are involved in exploring the spatial violations of the incongruent view of their legs. The observed combination of preferential looking, visual comparison, and visual–proprioceptive exploration indicates that infants are actively engaged in experiencing the discrepancies between the incongruent (novel) and the congruent relation between their own actions and the resulting direction of visible motion. Young infants are ready to learn about changes in the spatial calibration of vision and proprioception. This behavioral phenomenon corresponds to a basic attunement to intermodal invariants, which, we propose, form the developmental origins of self-perception.

The present demonstration of the infants' attunement to invariants of intermodal space suggests that from an early age infants are sensitive to information that eventually will enable them to specify themselves as a differentiated entity in the environment. However, further research is necessary to assess whether young infants discriminate the visual–proprioceptive experience of self-generated leg movements from that of other movements. A decisive test of such discrimination should involve a comparison between the infant's reaction to self-produced body movements and the reaction to object movements synchronous with those of the body. For example, the question is whether infants will show the same sensitivity regarding movement directionality when looking at either an online view of their own legs (present studies) or that of another object moving in synchrony with the legs' movements (e.g., point light display or mobile).

In addition to visual–proprioceptive experience of the body, there are other identifiable experiences involving different perceptual systems that might guide self-exploration. These experiences include touching one's own body (von Glasersfeld, 1988, p. 185), which involves the invariant experience of a double touch, or listening to one's own voice, which involves the invariant experience of an identical spatial relationship between the mouth as a sound source and the ears as receptors of these sounds, as well as the co-occurrence of proprioceptive feedback from the vocal track. Infants from birth experience these invariant relationships, which are directly linked to self-exploration. Neonates root toward stimulation on their cheek and spend a large proportion of waking time bringing their hand or hands to their mouth and face, experiencing the contrast between single and double touch (Rochat, 1993). They also orient to other sounds (Clifton, Morrongiello, Kulig, & Dowd, 1981) while listening to their own crying and cooing, henceforth experiencing the contrasts between self-produced sounds and other sounds. The early experience of such contrasts are viewed as the origins of perceptual learning about the self.

Future research is needed to further investigate the early detection of intermodal invariants specifying the self and how infants learn about them. Such research is necessary to account for the origins of self-cognition, and eventually to understand the central problem of the developmental transition from early self-exploration to later development of self-perception and the emergence of the conceptual self.

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