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Marie-Victorine Dumuids-Vernet, Joëlle Provasi, David Ian Anderson,
Marianne Barbu-Roth

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Neonatal Stepping in Relation to Terrestrial Optic Flow

Marianne Barbu-Roth

*Centre National de la Recherche Scientifique,
Université Paris Descartes*

Adeline Desprès

*Centre National de la Recherche Scientifique,
Université Paris Descartes*

Dominique Cabrol

*Assistance Publique - Hôpitaux de Paris, Université
Paris Descartes*

David Anderson

*San Francisco State University and University of
California, Berkeley*

Joëlle Provasi

Ecole Pratique des Hautes Etudes

Joseph J Campos

University of California, Berkeley

This experiment examined whether newborn stepping, a primitive form of bipedal locomotion, could be modulated by optical flow. Forty-eight 3-day-old infants were exposed to optical flows that were projected onto a horizontal surface above which the infants were suspended. Significantly more air steps were elicited by exposure to a terrestrial optical flow specifying forward translation than by a rotating optical flow or a static optical pattern. Thus, a rudimentary coupling between optical flow and stepping is present at birth, suggesting a precocious capacity in the newborn to perceive and utilize visual information specifying self-motion. The findings may help the early diagnosis of infants with visual or visual-motor deficits and the development of visually based interventions for disabled infants.

When newborns are supported in the upright position with the soles of their feet touching a rigid surface, they are able to make alternate stepping movements that bear a striking similarity to the mature form of human independent locomotion (Forssberg, 1985; Zelazo, Zelazo, & Kolb, 1972). Although there is still a prevailing bias toward viewing the stepping pattern as a tactically triggered “reflex” rather than a voluntary behavior (Fiorentino, 1981), several studies have demonstrated that neonatal stepping is a complex activity that is sensitive to numerous mechanical and contextual factors, including the infant’s morphology (Thelen, Fisher, & Ridley Johnson, 2002), the infant’s state of arousal (Thelen, Fisher, Ridley Johnson, & Griffin, 1982), the postural context in which stepping is tested (Jensen, Schneider, Ulrich, Zernicke, & Thelen, 1994), the nature of the tactile stimulation on the feet (Pang, Lam, & Yang, 2003; Thelen & Ulrich, 1991), and the

number of opportunities the infant has had to practice stepping (Zelazo, 1983). Despite considerable attention to the factors that can modify the stepping pattern, very little is known about the newborn’s capacity to adapt his or her stepping to various forms of perceptual information, such as those provided by the visual system. The lack of knowledge in this area might reflect the traditional assumption that vision is too immature to provide the infant with much of a connection to the external world at birth compared to the connections provided by the haptic, auditory, and vestibular systems. However, evidence for visually triggered and regulated locomotion in primitive species, such as the lobster (Davis & Ayers, 1972), combined with increasing evidence that the infant has rudimentary visual control over many early movements (van der Meer, van der Weel, & Lee, 1995; von Hofsten, 2004), suggests that early patterns like stepping might be more highly integrated with multiple sources of perceptual information than was once thought.

We reasoned that vision might be linked to the stepping pattern given the importance of optical flow for the regulation of locomotion in adults (Gibson, 1979; Warren, 1998) and given the links that have already been established between newborn stepping

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Correspondence concerning this article should be addressed to Marianne Barbu-Roth, Laboratoire Psychologie de la Perception, UMR 8158 CNRS, Université Paris Descartes, UFR Biomédicale, 45 rue des Saints Péres, 75006 Paris, France. Electronic mail may be sent to marianne.barburoth@parisdescartes.fr.

and independent walking (Cooke & Thelen, 1987; Zelazo et al., 1972). Moreover, when moving visual stimuli are large, high in contrast, and low in spatial frequency, it has been shown that infants as young as 3 days old are responsive to optic flows that move up to $30^\circ/s$. For example, neonates will retract their head in response to looming optic flows that expand centrally toward their face (Nanez & Yonas, 1994) or that move linearly past each side of their face (Jouen, Lepecq, Gapenne, & Bertenthal, 2000). Neonatal sensitivity to global optic flow has also been demonstrated for eye movements, with 3-day-old newborns showing ocular pursuit scaled to the direction and the velocity of patterns of vertical stripes moving horizontally (Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979; Lengyel, Weinacht, Charlier, & Gottlob, 1998; Roucoux, Culee, & Roucoux, 1983).

To test for the presence of a rudimentary coupling between vision and stepping, we examined whether optic flows that were low in spatial frequency and high in contrast could elicit air stepping in 3-day-old infants. The optic flows were projected onto a horizontally oriented surface above which the infant was held upright by an experimenter (see Figure 1). Though stepping on the table was also examined to ensure that infants were capable of making stepping movements, air stepping was chosen for the experimental conditions to determine whether stepping

could be induced or facilitated by the visual stimuli alone (i.e., in the absence of the tactile stimulation thought necessary to initiate and maintain stepping).

To control for the possibility that any large field optical motion might induce stepping, we used two different patterns of optic flow—one in which a checkerboard pattern moved toward the infant, specifying forward translation, and another in which a pinwheel rotated clockwise. The two patterns are shown in Figure 2. A control condition was also used in which the checkerboard pattern was static.

Method

Participants

The final sample consisted of forty-eight 3-day-old infants (half of each sex, mean age = 93.14 hr, $SD = 34.14$) with uncomplicated deliveries, mean weight of 3,441 gms ($SD = 509.1$), minimum Apgar score of 7 at 5 min after birth, and mean term of 39.7 weeks ($SD = 1.3$). The participants were predominantly middle class and 90% were Caucasian. The other 10% were of North or Central African descent. The mothers provided written informed consent prior to their infants' participation in the study.

All infants were tested just after feeding when awake and alert and were rated in Stage 3 (eyes open,

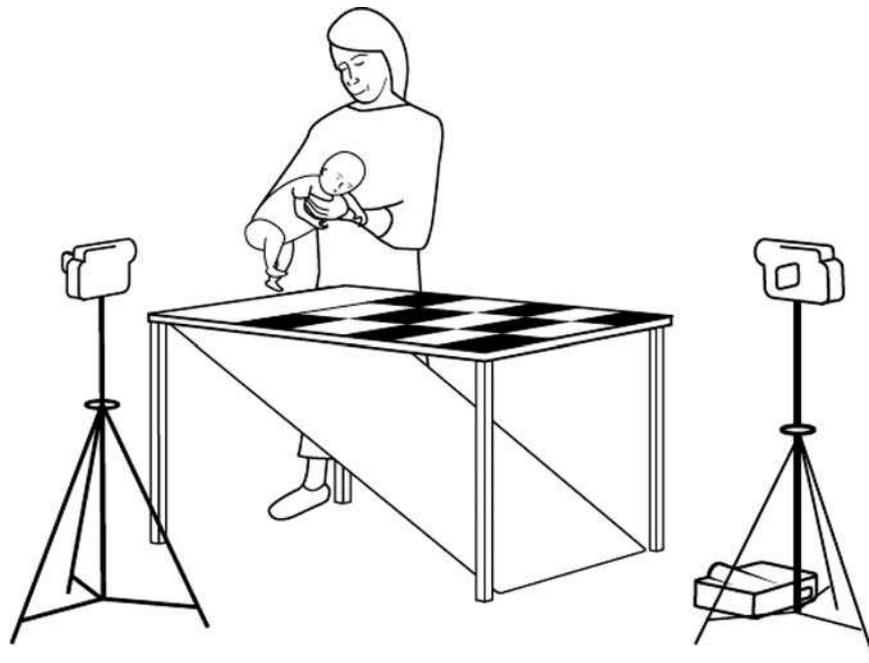


Figure 1. Cartoon showing the experimental setup.

Note. An experimenter held the baby above the table with the left hand supporting most of the baby's weight and the right hand lightly touching the base of the baby's sacrum. The index finger of the left hand was used to lightly support the baby's chin and to ensure the baby was looking at the visual stimuli on the table.

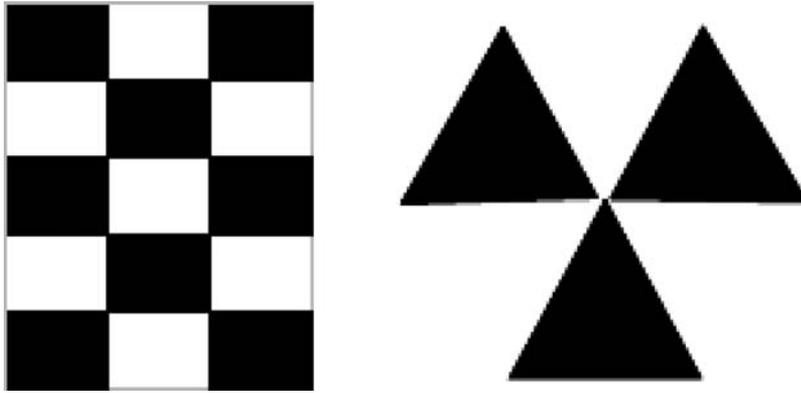


Figure 2. The visual stimuli.

Note. The checkerboard pattern was either static or translating toward the infant. The pinwheel rotated clockwise.

no movements) on Prechtl's (1974) scale just prior to testing. A total of 70 infants were tested in the experiment; however, the infants' data were not used if they cried more than an average of 30 s across the four experimental conditions, fell asleep, or did not look at the table surface for more than 30 s during any of the trials. Consequently, 22 infants were excluded from the analyses, yielding the final sample of 48.

Materials and Apparatus

The primary piece of apparatus was a 1 m × 1 m × 0.46 m (h × l × w) table, the surface of which was a solid rear projection screen. The visual stimuli were created using Pascal software and run on a PC computer connected to a video projector placed on the floor 2 m from a mirror (tilted at 45°) that reflected the images onto the surface. The visual stimulus subtended 74° of visual angle vertically and 54° horizontally from the infant's eye in the air stepping condition. Two digital video cameras (Sony DCR-HC38), positioned perpendicular to the sagittal and frontal planes, at a height of 1.2 m and 2 m away from the infant, captured each trial.

Projected visual stimuli. Two patterned visual stimuli were used. The first was a black-and-white checkerboard pattern with squares of 0.12 m projected size (approximate spatial frequency of 0.06 cycle/deg relative to the infants' eyes). This pattern was either static or moving toward the infant at 23°/s (approximate temporal frequency of 0.7 Hz relative to a stationary point). The velocity of 23°/s, equivalent to 0.17 m/s, was chosen because it falls within the range of mechanical velocities that yield optimal stepping rates in studies of infant treadmill stepping (Thelen & Ulrich, 1991) and is within the range of large visual field velocities that are well perceived by newborns (Jouen et al., 2000; Kremenitzer et al., 1979). The other

pattern consisted of six large black-and-white triangles arranged in a pinwheel of 0.30 m radius (approximate spatial frequency of 0.02 cycle/deg at the perimeter, systematically increasing to 1 cycle/deg at the center) that rotated clockwise at 0.17 m/s (approximately 38°/s). The temporal frequency varied from 0.3 Hz at the perimeter to 0 Hz at the center.

Procedure

The infants were tested in four 1-min conditions (with a 1-min break between conditions) that were randomly ordered across participants: (a) air stepping while held above the translating checkerboard pattern (translate), (b) air stepping while held above the static checkerboard pattern (static), (c) air stepping while held above the rotating pinwheel (rotate), and (d) stepping in place in contact with the horizontal surface while held in front of the static checkerboard pattern (tactile). Infants were not permitted to move forward in the latter condition to prevent them from receiving any optic flow associated with their forward translation on the surface.

All infants were held by one experimenter (E1) and monitored for alertness and direction of gaze by a second experimenter (E2) who was positioned opposite the first experimenter and close to the sagittal view camera. The videotapes were used to confirm alertness and gaze direction. E2 was also responsible for controlling the computer-generated visual stimuli. E1 was positioned on the left side of the table, slightly behind and to the left of the infant. This position was chosen for two reasons: (a) pilot work indicated that standing behind the infant and holding her under the armpits, as has been done classically in work on infant stepping, quickly resulted in crying when the infants were held above the surface, and (b) it was difficult to support the infant's head and ensure

gaze was directed toward the visual stimuli when the hands were under the infant's armpits. We found that infants could be supported well if the experimenter placed her left hand on the infant's chest with the experimenter's fingers supporting the infant's chin. The right hand was used to stabilize the infant, by applying light pressure to the infant's bottom when necessary but not to support the infant's weight. The infants were able to move their legs freely when held in this manner. To further facilitate viewing the visual stimulus, the infant's trunk was inclined forward 35–45° from the vertical. In the tactile condition, initiation of stepping was facilitated by first stimulating the "placing" response (i.e., by dragging the dorsal surface of the infant's foot across the edge of the table).

Results

Data Reduction

A step was defined as a cycle of flexion–extension of a leg independent of the time between flexion and extension. The angle between the trunk and the thigh had to pass beyond 90° in the flexion phase and back past 90° in the extension phase. The sagittal video view of the infant was used to code for stepping. A simple template grid was constructed on an overhead transparency sheet to facilitate coding. A thick band at the bottom of the video screen prevented coders from knowing the experimental condition. The duration of crying and the number of steps taken during crying and noncrying periods were also determined. There were two independent coders, one of whom was blind to the purpose of the experiment. The percentage agreement for number of steps taken during the tactile, translate, rotate, and static conditions were 0.94, 0.94, 0.93, and 0.92, respectively (e.g., in the tactile condition, the coders counted the same number of steps for 45 of the 48 babies who were included in the analysis), and the intraclass correlation coefficients (ICCs) were 0.99, 0.98, 0.98, and 0.96, respectively. The corresponding ICCs for duration of crying were 0.91, 0.94, 0.90, and 0.95. Data from the most experienced coder were subject to analysis.

Data Analysis

The data were analyzed using four separate repeated measures analyses of variance (ANOVAs) and planned comparisons were used to follow up on significant main effects. Significance was accepted at the .05 level. All the descriptive statistics for the dependent variables that were analyzed are presented in Table 1.

Table 1
Descriptive Statistics for all Dependent Variables Analyzed in the Experiment

	M	Minimum	Maximum	SD
Number of steps				
Tactile	8.81	0.00	34.00	7.76
Translate	8.60	0.00	29.00	8.31
Rotate	5.92	0.00	30.00	6.92
Static	5.52	0.00	24.00	5.17
Tactile L	4.52	0.00	20.00	4.22
Tactile R	4.29	0.00	14.00	4.02
Translate L	4.31	0.00	17.00	4.44
Translate R	4.29	0.00	14.00	4.38
Rotate L	2.92	0.00	14.00	3.52
Rotate R	3.00	0.00	18.00	3.70
Static L	2.67	0.00	11.00	2.77
Static R	2.85	0.00	13.00	3.00
Steps while crying				
Tactile cry	3.02	0.00	21.00	5.35
Tactile no cry	5.79	0.00	20.00	5.09
Translate cry	2.52	0.00	25.00	5.39
Translate no cry	6.08	0.00	25.00	6.64
Rotate cry	1.31	0.00	19.00	3.21
Rotate no cry	4.61	0.00	26.00	5.72
Static cry	1.40	0.00	14.00	3.02
Static no cry	4.12	0.00	24.00	4.68
Latency to step				
Tactile	7.49	0.44	47.71	10.48
Translate	12.46	0.88	55.59	14.38
Rotate	11.69	1.36	51.00	14.66
Static	13.63	1.60	52.64	15.32
Crying duration				
Tactile	9.67	0.00	53.36	14.78
Translate	6.02	0.00	46.64	12.46
Rotate	4.74	0.00	43.84	9.46
Static	5.37	0.00	50.44	11.51

Note. Latencies and durations are in seconds. L = left side; R = right side.

Total number of steps. It can be clearly seen in Table 1 that a greater number of steps were taken in the tactile and translate conditions compared to the other conditions. A 2 (side) × 4 (condition) ANOVA was run to determine whether the apparent differences between conditions were significant. The main effect for side was not significant, $F(1, 47) = 0.01$, *ns*, indicating that an equivalent number of right and left steps were taken, and there was no interaction between side and condition, $F(3, 141) = 0.26$, *ns*, indicating that an equivalent number of left and right steps was taken across conditions. Importantly, the differences between conditions apparent in Table 1 were confirmed by a significant main effect for condition, $F(3, 141) = 4.24$, $p < .05$, $\eta_p^2 = 0.09$. Three planned comparisons were done on the air

stepping conditions as they were the conditions of most interest in the current study. The first comparison confirmed that significantly more steps were taken in the Translate condition than in the Static condition, $F(1, 47) = 10.03, p < .05$, Cohen's $d = 0.45$. Of the 48 infants, 29 (60%) of them took more steps in the translate condition than the static condition. The second comparison showed that significantly more steps were taken in the translate condition than the Rotate condition, $F(1, 47) = 4.07, p < .05$, Cohen's $d = 0.35$, and 27 (56%) of the infants took more steps in the former condition than in the latter condition. Finally, the third comparison showed that the rotate and static conditions were not significantly different from each other, $F(1, 47) = 0.21, ns$.

It was interesting to note that the number of steps on the surface taken during the tactile condition was similar to the number of steps obtained in previous studies on newborn stepping over a 1-min interval (Thelen et al., 1982) even though the infant was prevented from moving forward and was held in a different manner. In contrast, suspending the infant above the static checkerboard surface inhibited stepping relative to allowing contact with the surface, although, consistent with previous observations on both human infants (Thelen & Fisher, 1982; Zelazo et al., 1972) and monkeys (Vilensky, Wilson, & Gankiewicz, 1989), there was some spontaneous air stepping. A planned comparison between the number of steps taken when the infant was in contact with the static checkerboard surface relative to when the infant was above the static checkerboard surface revealed a significant difference between the two conditions, $F(1, 47) = 9.04, p < .05$, Cohen's $d = 0.50$. This finding confirms that tactile stimulation facilitates stepping (in the absence of optic flow), although it is not needed to initiate stepping.

Latency. The second ANOVA was done to determine whether there were differences in the latency to initiate the first step in each of the conditions. The analysis revealed no significant differences in latency, $F(3, 141) = 1.90, ns$.

Duration of crying. The third ANOVA revealed that there were no differences in the duration of crying during each of the four conditions, $F(3, 141) = 2.14, ns$.

Steps while crying and not crying. Finally, a 4 (condition) $\times 2$ (steps while crying or not crying) ANOVA was run to determine if there were overall differences in the number of steps taken while crying or not crying or differences among conditions in the number of steps taken while crying or not crying. Given that infants were crying for only a small percentage of the trial duration, it was not surprising to find that significantly more steps were taken when the infant

was not crying than when the infant was crying, $F(1, 47) = 18.23, p < .05, \eta_p^2 = 0.28$. More importantly, however, the interaction between condition and steps taken while crying and not crying was not significant, $F(3, 141) = 0.25, ns$. In other words, there were no differences across conditions in the number of steps taken while the infant was crying or not crying.

Discussion

The clear evidence for a greater number of air steps in the translate condition compared to the other conditions of optical flow reveals that there is a rudimentary coupling between vision and air stepping in neonates. Moreover, there is a degree of specificity in the coupling given that only the optic flow that translated toward the infant induced a level of stepping above that observed with the static pattern. At the very least, the latter finding confirms that stepping cannot be induced by any large field optical motion.

Interestingly, arm movements that were correlated with leg movements were often observed during air stepping. It is possible that arm movements have not been observed in the classic tactile stepping paradigm used in previous studies because infants were typically held tightly under the armpits, thus preventing movement of the arms. Unfortunately, the arm movements themselves and the coupling between arm and leg movements were not quantifiable in the current experiment, although we do intend to address this issue in future experiments by conducting three-dimensional kinematic analyses of infants' leg and arm movements. Nevertheless, the qualitative observation of some coupling in the present study raises questions about how differentiated are the various locomotor patterns that have been documented at birth. For example, Thelen, Bradshaw, and Ward (1981) have argued that stepping and kicking are identical behaviors expressed in different postural contexts, raising the possibility that swimming, crawling, stepping, and kicking behaviors might all emerge from the same neuromuscular substrate and so might all be facilitated by visual stimulation in addition to tactile stimulation. Such speculation awaits confirmation by future empirical work.

In addition to testing whether other patterns of movement can be elicited or facilitated by exposure to optic flow, it would also be interesting to test whether there is any difference in stepping behavior if an infant is exposed to a translating optic flow that moves toward them versus one that moves away from them (specifying backward locomotion). We

suspect that there would be little difference in the number of steps taken in each condition, however, depending on the degree of specificity in the coupling between vision and locomotion at this very early age, it is quite possible that the stepping kinematics would be different. Such a finding would add further support to the current claim that a rudimentary coupling between vision and stepping exists at birth.

One potential limitation of the current experimental paradigm is that the experimenter holding the infant was not blind to the experimental condition in which the infant was being tested. For reasons of safety and compliance with hospital regulations and to ensure the infants were held the correct distance from the surface, it was not possible to blind the experimenter to the experimental condition, raising the possibility that the experimenter might have unintentionally biased the infants' behavior in each of the conditions. We think this possibility is extremely remote for two reasons: (a) the coders were not able to guess the condition in which the infant was being tested by watching how the experimenter held the infant and (b) we have tried to initiate or facilitate air stepping by holding infants in a variety of different ways and have failed on every attempt. Thus, if the experimenter were able to subtly bias the stepping behavior of the infant that feat would represent a remarkable discovery in its own right.

Why does optic flow elicit stepping behavior? At this time, there is not sufficient evidence to answer that question. However, we speculate that infants exposed to an optic flow that translates toward them have a sense of self-motion (vection) and step in an effort to calibrate the somatosensory and vestibular information that specify stasis with the visual proprioception that specifies locomotion. This explanation is quite similar to the one offered by Davis and Ayers (1972) to account for the induction and maintenance of locomotion that occurs when species such as the lobster are exposed to optic flows that move beneath them. These authors have argued that during self-initiated locomotion, visual feedback is actually positive, rather than negative, such that the visual feedback serves to reinforce and sustain the locomotor pattern once it is initiated. If so, then it should be possible to elicit locomotion by exposing animals to the positive visual feedback that typically accompanies self-initiated locomotion. Our explanation is also consistent with more recent work on adults showing that exposure to optic flows that are faster or slower than one's naturally chosen speed of locomotion can lead to unintentional gait modifications (Pailhous, Ferrandez, Fluckiger, & Baumberger, 1990; Prokop, Schubert, & Berger, 1997) and can modify the walk-

to-run and run-to-walk transition speeds (Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007).

The apparent ability of the newborn to discriminate an optic flow pattern specifying self-motion from one specifying stasis (the static pattern), or motion of an object in space (the pinwheel), suggests that a capacity for recognition of an implicit *ecological self*, as opposed to an *interpersonal self* (Neisser, 1991), is present from birth. In other words, the infant's behavior is relational; it is directed at a specific environmental demand, and the infant's behavior is differentiated in accordance with the task demand. However, like the coupling between vision and stepping, this capacity must be rudimentary, at best. We would argue that just as experience with the perceptual consequences of self-generated movements will lead to more robust coupling between perception and action, the same experiences will also lead to the development of a more robust conception of an ecological self, consistent with the arguments on the development of self-perception recently put forward by Rochat and Striano (2000). Longitudinal work is surely called for to test the veracity of these claims.

Finally, it is important to point out that the current findings have potentially important clinical implications because they suggest that a test of stepping (or other forms of locomotion) in response to optical flow might provide a way to diagnose visual and/or visual-motor deficits at birth or shortly thereafter. Furthermore, exposing infants to optical flows might facilitate the effectiveness of interventions designed to improve the locomotor skills of infants with disabilities. These exciting possibilities also await confirmation.

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