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Using social information to guide action: Infants' locomotion over slippery slopes

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ABSTRACT

In uncertain situations such as descending challenging slopes, social signals from caregivers can provide infants with important information for guiding action. Previous work showed that 18-month-old walking infants use social information selectively, only when risk of falling is uncertain. Experiment 1 was designed to alter infants' region of uncertainty for walking down slopes. Slippery Teflon-soled shoes drastically impaired 18-month-olds' ability to walk down slopes compared with walking barefoot or in standard crepe-soled shoes, shifting the region of uncertainty to a shallower range of slopes. In Experiment 2, infants wore Teflon-soled shoes while walking down slopes as their mothers encouraged and discouraged them from walking. Infants relied on social information on shallow slopes, even at 0°, where the probability of walking successfully was uncertain in the Teflon-soled shoes. Findings indicate that infants' use of social information is dynamically attuned to situational factors and the state of their current abilities.

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1. Introduction

In situations of uncertainty, infants often look to their caregivers to decide how to respond. Is the stranger friend or foe? Is the new toy funny or scary? Is the unfamiliar room inviting or threatening? Parents' social signals can tell infants whether to approach or avoid a new person, novel object, or questionable situation.

In the most commonly used paradigms in the social referencing literature, researchers observe infants' responses to an "ambiguous" toy (e.g., a motorized robot) or a strange person (Baldwin & Moses, 1996; Feinman, Roberts, Hsieh, Sawyer, & Swanson, 1992; Stenberg, 2009; Stenberg & Hagekull, 2007). Infants solicit information from their mothers by looking toward them or engaging them in social interaction. Mothers, in turn, provide infants with social information about how to interpret the stimulus by varying their facial expressions and vocalizations. By 12 months of age, infants change their affective displays and proximity to mother, toy, or person in accordance with the valence of mothers' messages (Hirschberg & Svejda, 1990; Hornik, Risenhoover, & Gunnar, 1987; Mumme, Fernald, & Herrera, 1996; Stenberg, 2009; Stenberg & Hagekull, 1997).

2. Using infant locomotion to study social cognition

Although infant locomotion may seem far afield from social cognition, locomotor tasks are especially useful for studying infants' sensitivity to social information. In locomotor tasks, researchers can parametrically vary the level of risk and ambiguity, whereas in other paradigms, researchers must rely on their own intuitions about ambiguity to select toys and strange people. Moreover, obstacles to locomotion elicit particularly clear approach/avoidance responses accompanied by a variety of social expressions and exploratory behaviors (Tamis-LeMonda & Adolph, 2005). Locomotion itself is a compelling attractor, and infants crawl or walk for the sheer joy of moving (Harlow & Mears, 1979). In the laboratory, they happily clamber up and down obstacles during dozens of trials for upwards of 60 min. At the same time, risk of falling is a powerful deterrent, so infants are highly motivated to guide locomotion adaptively. They consistently avoid obstacles that pose a clear threat of falling (Adolph, 1997).

Indeed, the most famous laboratory demonstration of the power of social information for guiding action is Sorce, Emde, Campos, and Klinnert's (1985) study of mothers' emotional signaling to their 12-month-olds on a modified "visual cliff". In the standard paradigm, infants face their mothers from one side of a glass-covered table (Walk & Gibson, 1961). On the "shallow" side of the apparatus, a patterned surface is attached to the underside of the safety glass so that it appears solid. On the "deep" side, the patterned surface is 102 cm below the glass, presenting the illusion of a large drop-off. In Sorce et al.'s study, the apparent drop-off was set to 30 cm, a height presumed to be ambiguous. Mothers stood at the far side of the obstacle and displayed positive and negative facial expressions. Infants who looked toward their mothers' faces were swayed by the emotional signals: they crossed when their mothers displayed positive expressions and avoided

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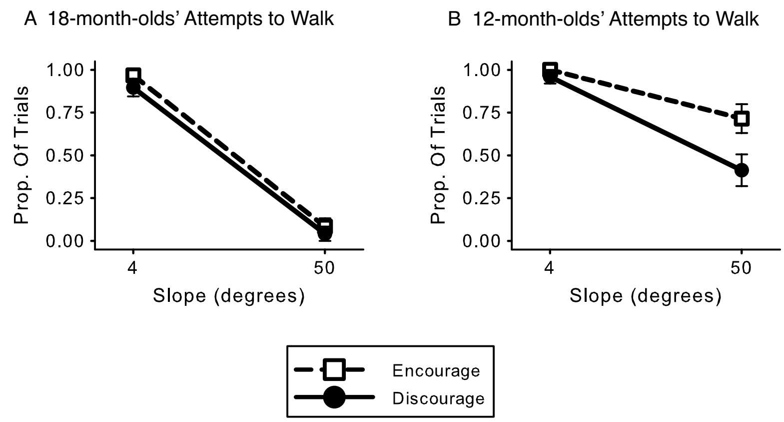

Fig. 1. Proportion of trials in which infants attempted to walk down slopes while barefoot: (A) 18-month-old experienced walkers; (B) 12-month-old novice walkers.

crossing when their mothers displayed negative expressions. In a subsequent study, 12-month-olds were faster in crossing the visual cliff in response to their mothers' vocal encouragements than to their positive facial expressions (in the voice-only condition, the mothers stood with their backs to the apparatus) and fastest when they could both hear and see their mothers, suggesting that the voice is an especially important channel for social signals (Vaish & Striano, 2004).

Of course, infants do not always seek their parents' counsel or take their unsolicited advice. When crawling infants are tested on the shallow side of the visual cliff, mothers' negative facial expressions are superfluous. Most 12-month-olds crossed without ever glancing at their mothers' faces, and those who viewed their mothers' fearful faces were not deterred (Sorce et al., 1985).

Likewise, encouragement is equally ineffective at swaying infants' responses on the deep side of the cliff; in the standard setup with a 90 cm drop-off, 12-month-old crawlers avoided crossing the deep side despite their mothers' smiles and verbal coaxing (Richards & Rader, 1983; Walk, 1966; Witherington, Campos, Anderson, Lejeune, & Seah, 2005).

More subtle variation of risk level reveals exquisitely selective use of social information for guiding locomotion down slopes (Tamis-LeMonda, Adolph, Lobo, Karasik, & Dimitropoulou, 2008). By 18 months of age, most infants are experienced walkers (infants begin walking around 12 months), but their skill varies widely. Some infants can walk down steep slopes (30°–40°), but others can manage only relatively shallow ones (10°–20°). Thus, a 25° slope can be safe for a more proficient walker (probability of success is 1.0) and impossible for a less skilled walker (probability of success is 0); but for an infant whose walking threshold is around 25°, the risk is uncertain (probability of success is approximately .50). By determining each infant's walking threshold – that is, their level of walking skill – risk can be normalized to skill level. Despite mothers' encouraging or discouraging facial expressions, gestures, words, and vocal intonations, 18-month-olds ignored their mothers' social signals when slopes were safe or impossible: they walked down safe slopes within their abilities but not down impossible slopes beyond their abilities (Fig. 1A). In contrast, on uncertain slopes around their individualized thresholds, infants deferred to their mothers' unsolicited social messages: they walked on 74% of trials when their mothers said go but on only 27% of trials when their mothers said no. The findings indicate that infants weigh social signals provided by their caregivers against perceptual information generated by their own exploratory activity, and social information outweighs perceptual information only when infants believe the latter is ambiguous. The fact that infants responded to their mothers' social signals only at the walking threshold indicates that they correctly recognized the uncertain risk at those increments.

3. Manipulating social signals to study infant locomotion

In the literature on locomotor development, Sorce et al. 's (Sorce et al., 1985) visual cliff study and Tamis-LeMonda et al.'s (2008) slope study are exceptions: the tradition in research on infant locomotion is to ignore the effects of social information. Typically, the goal is to assess infants' movements, rather than their responses to social information. Thus, caregivers merely function as a lure positioned at the far side of a walkway or obstacle, encouraging their infants to crawl or walk. The social context supports the task – infants are more likely to participate with caregivers in view – but since social information is held constant, researchers do not explicitly consider the role of caregivers' social signals in guiding motor actions. The consequence to the field is a conception of motor development as a solitary enterprise rather than a socially embedded process. More practically, researchers have failed to exploit caregivers' social signals as a potentially useful and readily available tool for investigating the development of infant locomotion. Differential responding to social information can give researchers purchase on infants' perception of affordances and their appreciation of motor risk.

An illustration of how manipulation of caregivers' social signals can inform research on infant locomotion concerns the specificity of motor experience—whether learning transfers from earlier to later developing postures. Several lines of evidence suggest that learning is specific to each posture in development. Novice infants faced with slopes, gaps, and real cliffs in unfamiliar sitting, crawling, cruising, and walking postures attempted impossible increments on repeated trials, requiring rescue by an experimenter to prevent injury from falling. After several weeks of experience with a new posture, infants distinguished safe from impossible increments and scaled their attempts to the conditional probability of success (Adolph, 1997, 2000; Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008; Kretch, Karasik, & Adolph, 2009). However, in each of these studies, caregivers provided only encouraging information, resulting in high attempt rates regardless of risk level in the novice infants. In other words, mothers' encouragement to descend may have led novices to discount the perceptual information specifying risk. But if we tested novice infants with both encouraging and discouraging social signals, we might be better able to detect their sensitivity to risk.

To test this possibility, 12-month-old experienced crawlers and novice walkers were observed on a range of safe, uncertain, and impossible slopes (Adolph et al., 2008). In half of the trials, mothers encouraged their infants to descend and in the other half, mothers discouraged them (as in Tamis-LeMonda et al., 2008). On impossible slopes, experienced crawlers ignored their mothers' advice; attempt rates were close to 0 in both social conditions.

However, social signals affected how novice walkers responded to impossible slopes such that, at the steepest increments, attempt rates decreased but were still perilously high (Fig. 1B). Despite mothers' discouraging frowns and knit eyebrows, prohibitive hand gestures and head shakes, and shouted "No's" and stern warnings to stop, infants attempted to walk on half of the trials. Thus, it is fair to conclude that under encouraging conditions, novice walkers were not merely walking because of their mothers' positive social message. Manipulating social signals tells us that novice walkers do have an inkling that extreme increments pose a potential threat of falling, otherwise their mothers' discouragement would have no effect on decisions at all, but they cannot yet scale their perceptual judgments to the limits of their own abilities.

4. Current studies

The current experiments took a two-pronged approach to the relations between social cognition and infant locomotion. We designed a new locomotor task to address the selectivity of infants' social cognition and we manipulated caregivers' social signals to examine flexibility in infant locomotion. Both approaches were integral to Experiment 2. Experiment 1 merely set the stage by establishing infants' walking skill under various friction conditions. The idea was to observe experienced 18-month-old walking infants in a slope task similar to the one used by Tamis-LeMonda et al. (2008) and Adolph et al. (2008), but to experimentally alter infants' ability to walk so that formerly uncertain slopes (between 20° and 30°) would become impossible and formerly safe slopes (less than 15°) would become uncertain. Experiment 1 established the utility of Teflon-soled shoes to pull off this feat, by pulling infants off their feet, so to speak, with slippery shoes on carpeted slopes. In Experiment 2, 18-month-olds wore Teflon-soled shoes and their mothers encouraged and discouraged them from walking down slopes spanning the range from shallow to steep (0°–50°).

The Teflon-soled shoes allowed us to address the question of whether 18-month-olds can update their assessment of uncertainty and adapt their use of social information accordingly. This question is important because infants' abilities and the properties of the environment are continually changing. An uncertain slope one week can be safe the next when walking skill improves. A safe slope under one set of conditions (e.g., walking barefoot) can be uncertain or impossible under a different set of conditions (walking in slippery shoes). Keeping pace with such changes in affordances requires real-time updating of risk and dynamically attuned use of social information.

Simultaneously, we manipulated mothers' social signals – mothers both encouraged and discouraged their infants to walk down slopes – to examine two outstanding issues in the development of infant locomotion. One issue concerns the effects of locomotor experience in learning to perceive affordances. Normally, walking experience and walking skill are highly correlated, such that more experienced infants display higher walking thresholds than less experienced infants (Adolph, 1997; Tamis-LeMonda et al., 2008). Thus, an alternative explanation for high error rates in novice walkers on impossible increments is that poor skill overtaxed or interfered with their ability to detect affordances; while trying to keep balance in their new, upright posture, they were unable to focus attention on perceptual information for gauging risk. If we could transform experienced, proficient 18-month-old walkers into poorly skilled walkers while keeping the upright posture constant, then we could disentangle the effect of walking experience from that of walking skill.

A second issue concerns infants' sensitivity to friction underfoot. Several previous experiments indicated that experienced 14- and 15-month-old walking infants respond only to slant, not to friction, as they approach impossible slopes, whereas adults use information for slip underfoot in guiding locomotion down slopes (Adolph, Eppler, & Joh, 2010; Joh, Adolph, Narayanan, & Dietz, 2007). But, in previous work, the infants were tested only under encouraging conditions. If we tested infants with both encouraging and discouraging social signals, we might better detect their sensitivity to friction as an important component in affordances for walking down slopes.

Assuming a decrement in infants' walking skill due to the slippery shoes, several results were possible. Despite several months of walking experience, 18-month-old experienced walkers might behave more like 12-month-old novice walkers and use social signals selectively only at the steepest increments (see Fig. 1). Such a finding would suggest that the reason infants display high error rates on impossible increments in novice postures is due to low levels of motor skill, interfering with their ability to focus attention on perceptual information. In this case, errors would not be explained by insufficient walking experience, and prior conclusions about novice infants' inability to detect affordances would need to be revisited. A second possibility is that the 18-month-olds would respond only to the degree of slant, using social signals selectively only at the mid-range of slopes, where their abilities would be uncertain while walking barefoot or in normal shoes. This result would suggest that infants do not dynamically update their assessment of uncertainty, and it would corroborate previous findings that infants are insensitive to variations in friction beneath their feet. A third possibility is that the infants would use their mothers' social signals selectively only at the shallowest range of slopes. This finding would be most exciting because it would suggest that 18-month-olds dynamically update their assessment of uncertainty, that new walkers err on risky increments due to insufficient walking experience (not poor walking skill), and that infants, like adults, are sensitive to friction forces in the shoe–floor interface and can predict the exaggerated effects of low friction on relatively shallow slopes.

5. Experiment 1: changing the region of uncertainty

We knew from previous work with 14- and 15-month-olds and adults that low friction dramatically hampers walking skill on slopes. Experiment 1 was designed to establish the extent of the decrement in 18-month-old walkers so that we could determine a new region of uncertainty for Experiment 2. We manipulated friction conditions with slippery shoes rather than a slippery walking surface to make the situation more ambiguous: infants can see the walking surface, but they cannot see the soles of their shoes; effects of friction must be perceived based on the feeling of slip at the shoe–floor interface (Joh et al., 2007). Thus, the apparatus was covered with a familiar carpeted surface and infants wore slippery Teflon-soled shoes. To provide a comparison with the slippery shoes and to replicate previous results with this age group (Adolph, 1997; Tamis-LeMonda et al., 2008), we tested infants walking barefoot and in crepe-soled shoes. Similar walking thresholds in the barefoot and in crepe-soled shoe conditions would also rule out the alternative explanation that decrements in the thresholds of infants wearing the Teflon-soled shoes were due to wearing new (possibly uncomfortable or ill-fitting) shoes rather than due to low friction.

5.1. Method

Participants. Families were recruited from the greater metropolitan area through visits to the maternity ward of local hospitals and purchased mailing lists. All infants were healthy and born at term. Most families were white, middle-class, and educated. Parents received framed photographs of their infants to commemorate their visit.

Seventy-eight infants participated in one of three walking conditions: Teflon-soled shoes (13 boys, 9 girls), barefoot (18 boys, 22 girls), and crepe-soled shoes (8 boys, 8 girls). Due to practical constraints of recruiting participants, infants wearing Teflon-soled shoes were slightly older ($M = 18.82$ months, $SD = 0.41$) than infants walking barefoot ($M = 18.04$ months, $SD = 0.27$) and infants wearing crepe-soled shoes ($M = 18.07$ months, $SD = 0.16$); $F(2, 60) = 53.13$, $p < .001$. Post hoc comparisons confirmed these age differences ($p < .001$). Infants in the barefoot and crepe-soled groups were of similar ages ($p > .05$). Parents reported their infants' walking experience (the first day that they witnessed infants walking 10 ft without stopping or falling) in the context of a structured interview, using calendars and baby books to augment their memories. As a consequence of being a few weeks older, infants wearing Teflon-soled shoes had slightly more walking experience ($M = 6.54$ months, $SD = 1.63$) than infants wearing rubber-soled shoes ($M = 5.08$ months, $SD = 1.45$); $F(2, 60) = 3.77$, $p < .05$. Post hoc comparisons confirmed this difference in walking experience ($p < .05$). Walking experience in the barefoot group ($M = 5.89$ months, $SD = 1.69$) did not differ from either of the other groups. We considered the slight age and experience advantage of infants in the Teflon group to be acceptable because any impairment due to the Teflon-soled shoes would be conservatively biased—that is, if anything, slightly older and more experienced infants would be expected to show smaller impairments due to the slippery shoes. Seventeen (Teflon = 4, barefoot = 10, crepe = 3) additional infants did not contribute data due to fussiness ($N = 12$) or experimenter error ($N = 5$).

Sloping walkway and slippery shoes. We tested infants' walking skill on a wooden walkway with an adjustable slope (Fig. 2). A sloping ramp (86 cm wide × 91 cm long) was connected with piano hinges to flat starting (86 cm wide × 182 cm long) and landing platforms (86 cm wide × 91 cm long) to form a continuous walking surface. An electric motor, operated with a push-button remote, adjusted the slope of the ramp from 0° to 90° in 2° increments by raising and lowering the height of the landing platform from 116 to 25 cm. The height of the starting platform remained fixed at 116 cm. A protractor on one side of the walkway indicated the degree of slope. Nets spanned the sides of the walkway as a safety precaution, and the surface was lined with plush carpet. A raised catwalk on one side of the walkway provided the experimenter with easy access to infants in case they fell.

We constructed Teflon- and crepe-soled shoes from flat-soled, commercial infant sneakers (infant sizes 3–9). We attached pieces of slippery Teflon material (1.75 mm thick, 20 g) or standard shoe rubber (2 mm thick, 16 g) to the toe and heel sections of the shoe sole, allowing the shoe to flex around the arch when infants bent their feet. All of the shoes looked and felt like typical infants' sneakers. It was only apparent to infants whether the shoe/carpet interface was slippery after they began walking.

Procedure. We used a psychophysical procedure developed in earlier work to estimate each infant's ability to walk down slopes (Adolph, 1997; Adolph et al., 2008; Tamis-LeMonda et al., 2008). Trials began with infants standing on the starting platform. Mothers stood at the end of the landing platform and encouraged their infants to walk down, offering toys and dry cereal as incentives. An experimenter stood on the raised catwalk and followed alongside infants to ensure their safety. An assistant panned a camera from a side view of the walkway. A second camera recorded the degree of slant from the protractor. Both camera views were mixed onto a single video frame. Trials lasted until infants reached the landing platform or 30 s if they avoided descent. Sessions lasted approximately 90 min.

Protocols began with four consecutive trials at 0° to teach the infants the game of crossing the walkway to their caregivers and to acclimatize them to the height of the starting platform. Then, beginning with an easy baseline slope of 4°, the experimenter increased or decreased the degree of slope based on the outcome

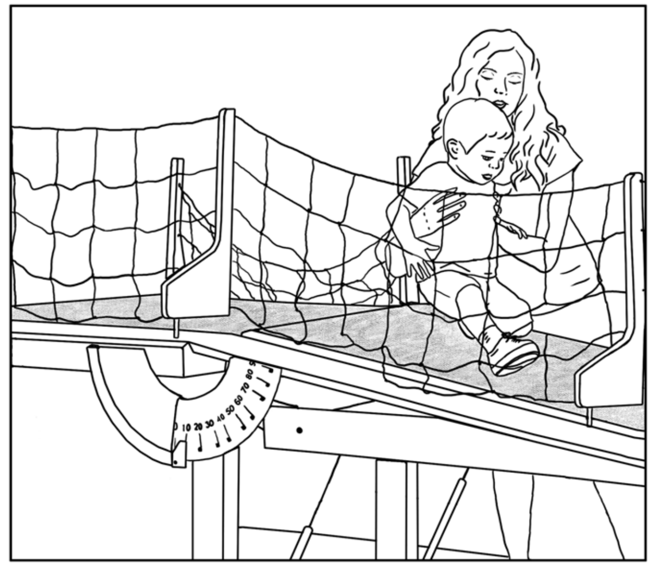

Fig. 2. Walkway with an adjustable slope. An experimenter (shown) followed alongside infants to ensure their safety. Mothers and another experimenter (not pictured) stood at the end of the landing platform, coaxing infants to walk.

of the previous trial. Trials were coded online as a success (walked safely), failure (tried to walk but fell), or refusal to walk (slid down or avoided going). After each successful trial, the experimenter increased the slope by 6°. After failures, the experimenter presented infants with the baseline 4° slope to renew their motivation to walk, and then re-entered the protocol with a slope 4° shallower than the previous success. After refusals, infants received the baseline slope and then trials were repeated, so that thresholds were determined based only on the ratio of successes to failures. The rule of "plus 6°, minus 4°" continued until meeting a ≥ 0.67 stopping criterion for estimating the walking threshold: the steepest slope at which the ratio of successes to failures was at least 0.67 and $< .67$ at the next 2°, 4°, and 6° increments. Fewer trials were required for shallower thresholds and more trials were required for steeper thresholds and protocols with frequent refusals to walk. The total number of trials ranged from 17 to 63, $M = 33.14$.

We obtained useable protocols from every infant in the Teflon-soled shoe group—presumably because the slippery shoes caused them to fall as slopes became challenging. However, on 12 protocols in the barefoot group and 3 protocols in the crepe-soled shoe group, infants never fell; these protocols were not analyzed because the walking thresholds would be underestimated. Infants who never fell did not differ from infants who did exhibit failures in terms of their age or walking experience. Thus, the final sample consisted of 63 infants, 22 wearing Teflon-soled shoes, 28 walking barefoot, and 13 wearing crepe-soled shoes.

Video coding. A primary coder rescored trials from video to verify the online scoring. A computerized video coding system, OpenSHAPA (openSHAPA.org), allowed frame-by-frame viewing of the video (Sanderson et al., 1994). Trials were rescored as *success*, *failure*, and *refusal*, as described above. A second coder scored 25% of the trials to verify inter-rater reliability. Inter-rater agreement was 96.7% ($\kappa = .95$, $p < .001$). Disagreements were resolved through discussion. Only threshold estimates derived from video coding were used in analyses.

5.2. Results and discussion

Teflon-soled shoes grossly impaired infants' ability to walk down slopes. Despite their slight advantage in terms of age and

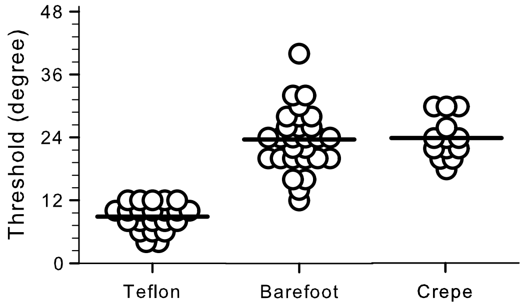

Fig. 3. Distribution of walking thresholds. Each symbol represents an individual infant's walking threshold; horizontal lines on each plot represent mean values.

experience, infants in the Teflon group managed only $M = 8.91°$ slopes ($SD = 2.52$). Average walking thresholds in the barefoot ($M = 23.64°$, $SD = 5.94$) and crepe-soled shoe groups ($M = 24.00°$, $SD = 4.00$) were almost three times as steep; $F(2, 60) = 74.10$; $p < .01$. As shown in Fig. 3, while wearing the slippery shoes, the distribution of walking thresholds was dramatically displaced to a shallower range of slopes. In fact, only data from one infant in the barefoot group overlapped the distribution of thresholds in the Teflon-soled shoe group. Post hoc comparisons confirmed higher walking thresholds for the barefoot and crepe-soled groups as compared to the Teflon-soled group ($p < .001$). The similarity in average thresholds between the barefoot and crepe-soled shoe groups suggests that the decrement in the Teflon-soled shoe group resulted from the slippery soles, not the novelty or potential discomfort of wearing new shoes. Moreover, adults in previous work showed similar effects of footgear on walking skill while wearing adult-sized versions of the Teflon- and crepe-soled shoes (Joh et al., 2007), and 14-month-olds walking in nylon tights over slippery vinyl surfaces showed similar decrements in walking skill due to low-friction conditions (Adolph et al., 2010).

Average thresholds were not the only outcome affected by the Teflon-soled shoes: the footgear also affected the variability around the group means. As in previous research with 18-month-olds (Tamis-LeMonda et al., 2008), infants showed a wide range of walking thresholds while walking barefoot (12°–40°). In contrast, as illustrated in Fig. 3, infants showed a compressed range of thresholds while walking in Teflon- (4°–12°) and crepe-soled shoes (18°–30°). The narrowed range in the Teflon group is easily explained by the difficulty of walking down slopes in the slippery shoes. Even small movements that threw infants slightly off balance caused them to fall. Similarly, 14-month-olds in previous work showed a compressed range of walking thresholds in low-friction (0°–6°) compared with high-friction conditions (6°–26°) (Adolph et al., 2010). But why the compressed range in the crepe-shoe condition? Possibly, infants did not display thresholds in the lower end of the barefoot range because the crepe soles gave the less skilled walkers more traction than being barefoot, and infants did not display thresholds in the higher end of the barefoot range because the shoes precluded the more skilled walkers from gaining additional traction by gripping the surface of the slope with their toes (McGraw, 1935).

6. Experiment 2: use of social information

In previous work, experienced 18-month-old walkers used social information selectively only at the region of uncertainty around their walking thresholds (Tamis-LeMonda et al., 2008). But those infants were walking barefoot and their walking thresholds were in a mid-range of slopes (20°–30°). The question here was what would happen when we altered infants' walking skill with the Teflon-soled shoes. Would 18-month-olds be transformed into novice walkers and behave like the 12-month-olds in previous work (Adolph et al., 2008)? Would they act oblivious to the feeling of slip, as we had observed in 14-month-olds previously (Adolph et al., 2010), and simply respond to the degree of slant? Or would they update their assessment of uncertain risk when walking down slopes wearing slippery shoes?

As in previous research (Adolph et al., 2008; Tamis-LeMonda et al., 2008), the primary outcome measure was whether infants attempted to walk. In addition, we scored infants' responses on trials where they refused to walk to determine whether mothers' discouraging messages caused infants to avoid descent by remaining on the starting platform or whether infants used alternative sliding positions to descend. We also scored infants' spontaneous exploratory activity – latency and touching – to describe how they generated perceptual information for potential risk, and their social expressions – positive and negative facial expressions and vocalizations – to determine whether infants' social expressions mirrored mothers' social signals and/or accompanied risk avoidance.

6.1. Method

Participants. Twenty-four 18-month-olds ($M = 18.44$ months, $SD = 0.44$; 12 boys and 12 girls) and their mothers were recruited as in Experiment 1. Walking experience ($M = 5.93$ months, $SD = 1.77$) was similar to that of the infants in Experiment 1. The infants were relatively experienced walkers. They were primarily white and from middle-class homes. Six additional infants did not complete testing due to fussiness ($N = 5$) or experimenter error ($N = 1$).

Walkway and procedure. Infants wore the same slippery, Teflon-soled shoes and walked over the same carpeted, sloping walkway used in Experiment 1. As before, an experimenter followed alongside infants to ensure their safety. Sessions lasted approximately 90 min. Because the range of thresholds was so compressed in the Teflon-soled group in Experiment 1, for Experiment 2, it was not necessary to estimate thresholds on an individualized basis before testing the effects of social signals (as in Adolph et al., 2008; Tamis-LeMonda et al., 2008). Instead, we could safely assume that infants would only be able to manage very shallow slopes. Thus, testing consisted of four blocks of 11 trials distributed in 5° increments from 0° to 50° in 1 of 4 random trial orders. The shallowest slopes (0°, 5°, 10°, and 15°) included 100% of walking thresholds from infants in the Teflon group in Experiment 1—presumably uncertain for infants in Experiment 2. The mid-range of slopes (20°, 25°, 30°, and 35°) included 93% of thresholds from infants in the barefoot and crepe groups in Experiment 1—safe under normal footgear conditions, but impossible while wearing the slippery shoes. The steep range of slopes (40°, 45°, and 50°) was impossible for all but one barefoot child in Experiment 1—that is, impossible in any footgear.

Trial blocks alternated between encourage and discourage conditions. Condition order and trial presentation orders were counterbalanced across infants. Trials lasted 30 s or until infants initiated descent, whichever occurred first. An assistant panned a camera from the side of the walkway to record infants' whole body movements, a second assistant recorded a close-up view of infants' faces from the bottom of the walkway, and a third camera recorded the degree of slant from the protractor attached to the walkway. A shotgun microphone mounted on the ceiling recorded infants' vocalizations. The camera views and audio track were mixed onto a single video frame.

Protocols began with four consecutive warm-up trials on the flat 0° walkway to ensure that they could walk in the slippery shoes and to acclimatize them to the raised walkway. As in previous work (Adolph et al., 2008; Tamis-LeMonda et al., 2008), on test trials, mothers were instructed to encourage/discourage their infants to walk down the slopes using words, vocal intonations, facial expressions, gestures, and body language in whatever way felt most natural. In the encourage condition, mothers were instructed to "get their infants to try to walk down the slopes"; they should "treat the situation as if they were encouraging their infants to tackle a new challenge such as taking their first walking steps or jumping into a caregivers' arms at the swimming pool". In the discourage condition, mothers were instructed to "prevent their infants from trying to walk down the slopes"; they should "treat the slope as if it were a sheet of ice that would jeopardize infants' safety". Mothers were told to disregard the steepness of the slopes when delivering their messages. Previous work verified that the mothers' behaviors varied by social incentive condition but not by slant (Karasik, Tamis-LeMonda, Adolph, & Dimitropoulou, 2008; Tamis-LeMonda et al., 2008).

Mothers sat on a raised platform adjacent to the landing platform, at infants' eye level but out of reach (Fig. 4). At the beginning of each trial, the experimenter held infants on the starting platform. After infants faced their mothers, an assistant rang a bell to signal mothers to begin encouraging or discouraging. The experimenter released the infant after 2 s and mothers continued to deliver their social message.

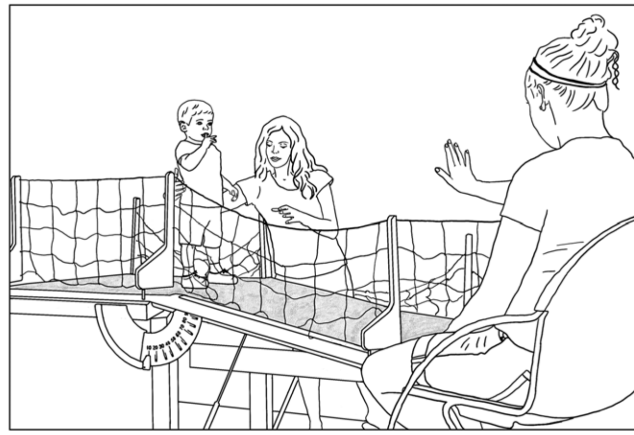

Fig. 4. Location of experimenter and mother during test trials while infants walked in Teflon-soled shoes. Mothers sat on a raised platform adjacent to the landing platform. An experimenter followed alongside infants to ensure their safety.

Video coding. A primary coder scored each trial from video using OpenSHAPA. A secondary coder scored 25% of each infant's data to verify inter-rater reliability. Disagreements between coders were resolved through discussion. *Attempts to walk* were scored as successes, failures, and refusals, as described above. Coders agreed on 96.5% of trials ($\kappa = .94$). On trials scored as refusals, coders determined whether infants slid down (sitting, head first prone, or feet first backing) or avoided descent for the duration of the trial (98.5% agreement, $\kappa = .98$). *Latency* to descend was scored from the start of the trial until infants initiated descent, and included the time infants explored slopes by looking and touching. Latency could range from 0 s (immediate decision) to 30 s (maximum trial length). The correlation between coders' scores was $r(184) = .98$, $p < .001$. Infants nearly always used their feet, not their hands, to explore slopes by *touching*. Thus, tactile exploration included rubbing the feet against the slope, rocking back and forth with feet straddling the brink, or taking tiny steps at the edge of the slope (99.5% agreement, $\kappa = .83$). Coders scored *negative vocalizations* as whining, whimpering, and crying (97.0% agreement, $\kappa = .90$) and *negative facial expressions* as frowns, pouts, and downward curls of the mouth (94.5% agreement, $\kappa = .83$). All other vocalizations and facial expressions were scored as *positive/neutral* (92.0% agreement, $\kappa = .84$; and 100% agreement $\kappa = 1.0$, respectively). Both negative and positive/neutral social expressions could occur in one trial.

6.2. Results and discussion

Preliminary analyses showed no effects of presentation order, so data were collapsed across orders for subsequent analyses. Result graphs are shown with all 11 slopes (0°–50°), but for statistical analyses, we compared infants' behaviors across shallow (0°–15°), intermediate (20°–35°), and steep slopes (40°–50°), based on the range of thresholds obtained in Experiment 1. Consistent with Experiment 1, success rates were 92% at 0°, 86% at 5°, 32% at 10°, and 0% on steeper slopes. For each outcome measure, data were subjected to a 2 (social message condition: encourage and discourage) × 3 (risk levels: shallow, intermediate, and steep) repeated measures ANOVA. Interactions were followed up with paired t tests between conditions at each risk level (with Bonferroni-adjusted alpha levels of $p < .02$).

Attempts to walk. Attempts to walk were more frequent in the encourage condition and decreased linearly with risk from 1.0 at 0° to .17 at 50° (open square symbols in Fig. 5A). If we had only tested infants with encouraging social signals (as in Adolph et al., 2010), we would have concluded that infants responded only to slant, not to friction. Fortunately, here we also tested infants with discouraging social signals. As shown by the closed circle symbols in Fig. 5A, infants' responses to discouraging social signals revealed sensitivity to the low-friction manipulation: at 0°, when mothers discouraged, attempt rates dropped from 1.0 to .59 and decreased steadily across risk levels. In fact, mothers' social messages had the largest effect on infants' attempts at the shallowest slopes, indicating that infants had updated their assessment of uncertainty in accord with the novel situation of walking in slippery shoes and that they used social information accordingly.

As in previous work (Tamis-LeMonda et al., 2008), infants continued to defer to their mothers' messages at the mid-range of slopes, where risk would normally be uncertain, but where walking was now impossible. But, unlike the 12-month-old novice walkers shown in Fig. 1B (Adolph et al., 2008), 18-month-olds in slippery shoes ignored their mothers' social signals at the steepest range of slopes, indicating that poor walking skill is not the factor responsible for high error rates in novice walkers. This interpretation is corroborated by similar evidence from 14-month-olds wearing heavy shoulder packs that hindered their walking skill; infants flexibly updated their perception of uncertain risk, treating the same degrees of slope as safe while wearing featherweight packs but as impossible while wearing lead-weighted packs (Adolph & Avolio, 2000).

The ANOVA confirmed main effects for condition, $F(1, 23) = 19.26$, $p < .001$, partial $\eta^2 = .46$; risk level, $F(2, 46) = 42.64$, $p < .001$, partial $\eta^2 = .65$; and a condition by risk level interaction, $F(2, 46) = 13.35$, $p < .001$, partial $\eta^2 = .37$. Post hoc comparisons confirmed higher attempt rates when mothers encouraged at the shallow and intermediate ranges of slopes (Ms $=$ .83 versus .46 and .42 versus .25 for encouraging and discouraging messages at the shallow and intermediate ranges of slopes, respectively).

Avoidance. A second source of evidence that infants updated their perception of uncertainty and used social information selectively is their high rate of avoidance on shallow slopes. On trials where infants refused to walk, they could slide down (in sitting, backing, or prone positions) or avoid going entirely. Overall, infants avoided descent on 57.2% of refusal trials. The striking finding is the high rate of avoidance on the 0°–15° slopes when mothers discouraged ($M = .45$) compared to when they encouraged ($M = .09$) and the fact that mothers were equally successful at keeping infants on the starting platform across risk levels in the discouraging but not the encouraging condition (Ms $= .48$ versus .26 and .52 versus .27, for discouraging versus encouraging at the intermediate and steepest slopes, respectively).

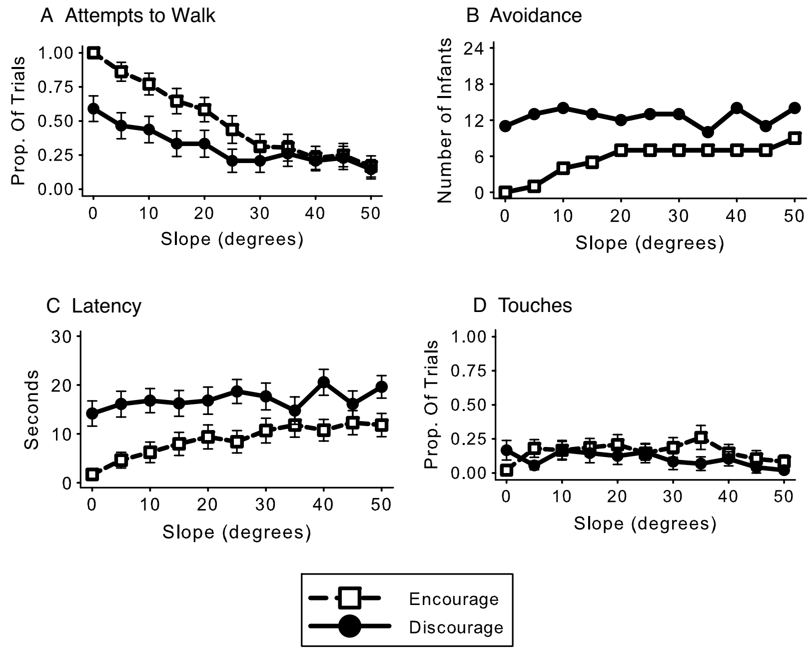

Fig. 5. Walking attempts and exploratory behaviors. (A) Proportion of trials in which infants attempted to walk down slopes; (B) number of infants that avoided descent and remained on the starting platform for the duration of the trial; (C) latency to begin descent; (D) proportion of trials in which infants touched the sloping section of the walkway.

Indeed, avoidance rates mirrored attempt rates for both types of social signals. Fig. 5B shows that half of the sample (the *y*-axis shows the number of infants) avoided descent on at least one trial at every risk level in the discouraging condition. When mothers encouraged the infants to walk, infants refused to do so at the steepest increments, but they frequently slid down (65% of refusal trials) rather than avoiding descent, indicating that the encouraging social signals did affect their behavior by prompting them to find alternative means of descent. An ANOVA on the proportion of avoidance trials revealed main effects for condition, $F(1, 23) = 18.88$, $p < .001$, $\eta^2 = .45$; risk level, $F(1, 46) = 6.89$, $p < .01$, $\eta^2 = .23$; and an interaction between condition and risk, $F(2, 46) = 3.74$, $p < .05$, $\eta^2 = .14$. Post hoc comparisons showed higher rates of avoidance when mothers discouraged at every risk level, with the largest disparity at the shallow range of slopes.

Latency. As in previous work (e.g., Adolph, 1997; Tamis-LeMonda et al., 2008), latency to descend increased with risk in the encouraging condition (Fig. 5C). But mothers' social signals had differential effects. Regardless of whether they ultimately decided to walk, slide, or avoid, at every risk level, infants hesitated for longer durations while formulating their decisions during discouragement ($M = 17.3$ s) compared with encouragement ($M = 8.89$ s). During the time that they hesitated, infants looked at the slope and at their mothers and occasionally called to their mothers. Most important, as shown in the figure, latency mirrored attempt rates. The largest disparity between encouraging and discouraging social signals was at the shallowest range of slopes. Remarkably, discouraging social signals kept infants poised in indecision on the starting platform at 0° (14.67 s) for nearly the same duration as at 50° (18.67 s). As a comparison, when mothers encouraged, infants hesitated for only 1.76 s at 0° before running down; at 50°, they hesitated for 11.74 s and refused to walk. An ANOVA confirmed main effects for condition, $F(1, 23) = 30.61$, $p < .001$, $\eta^2 = .57$; risk level, $F(1, 46) = 15.35$, $p < .001$, $\eta^2 = .40$; and an interaction between the two factors, $F(2, 46) = 4.38$, $p < .05$, $\eta^2 = .16$. Post hoc comparisons showed differences between social message conditions at every risk level, with the largest difference at the shallowest slopes.

Touching. In contrast to previous work with experienced walkers (Adolph, 1997; Adolph & Avolio, 2000; Tamis-LeMonda et al., 2008), touching was infrequent at every risk level, regardless of social message (Fig. 5D). The ANOVA showed no effects for risk level, $F(2, 46) = 1.87$, $p > .05$; social message, $F(1, 23) = 0.25$, $p > .05$; or interaction $F(2, 46) = 0.86$, $p > .05$. Overall, infants touched on only 12.8% of trials, and four infants never touched. Possibly, touching was constrained by the difficulty of keeping balance in the slippery shoes while poking one foot out or rocking at the brink. Fourteen- and 15-month-old infants also showed depressed levels of tactile exploration on slippery slopes compared with high friction conditions (Adolph et al., 2010).

Social expressions. As shown in Fig. 6A–B, across conditions and risk levels, infants consistently displayed positive–neutral facial expressions ($M = .99$) and rarely displayed negative facial expressions ($M = .11$). Six infants never produced a frown, pout, or downward mouth curl, and negative facial expressions only exceeded .50 at any increment for two infants. These two were not indiscriminate "cry babies" because they also displayed positive–neutral facial expressions at the same increments. The ANOVAs showed no effects of social condition, $F(1, 22) = 3.01$, $p > .05$; risk level, $F(2, 44) = 0.38$, $p > .05$; or their interaction, $F(2, 44) = 0.38$, $p > .05$, on infants' positive–neutral facial expressions or negative facial expressions, $Fs = 0.18, 0.57, 0.14$, $ps > .05$, respectively. The results corroborate previous findings that infants produce positive-neutral, not negative, facial expressions while refusing risky increments, even when their mothers display negative social signals (Adolph et al., 2008; Sorce et al., 1985; Tamis-LeMonda et al., 2008).

Infants' vocalizations were similarly lacking in negativity (compare Fig. 6C–D). Overall, infants vocalized on 40.3% of trials. Of these, 29.2% contained only positive–neutral vocalizations, 4.5% contained only negative vocalizations, and 6.5% contained both. Nine infants never produced a negative vocalization.

As shown in Fig. 6C, across risk levels, positive–neutral vocalizations were more prevalent when mothers discouraged ($M = .41$) than when they encouraged ($M = .27$). At first sight, the result seems counterintuitive, but it makes sense when

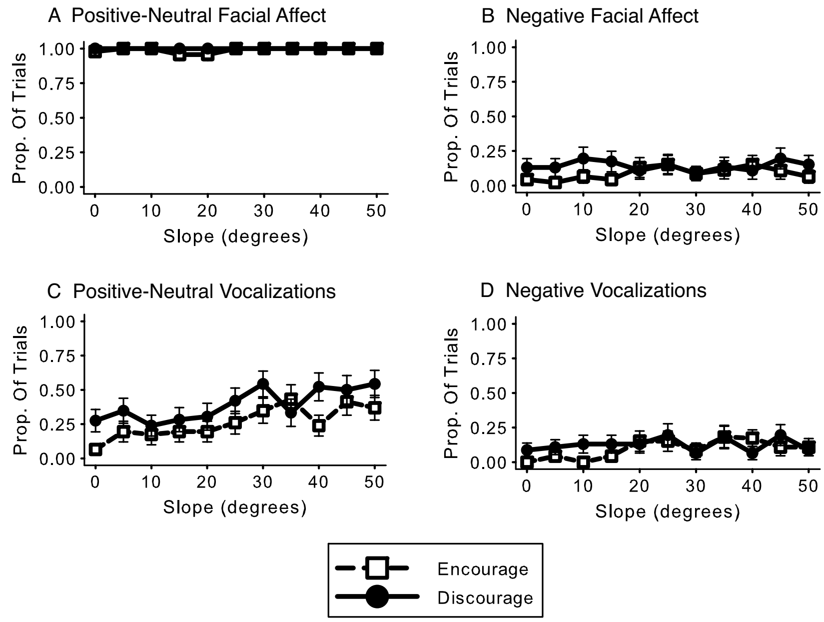

Fig. 6. Infants' social expressions. Proportion of trials in which infants (A) displayed positive–neutral facial expressions; (B) displayed negative facial expressions, (C) emitted positive–neutral vocalizations; and (D) emitted negative vocalizations.

considering vocalizations and latency together. Given the low rate of negative vocalizations overall and the fact that mothers kept the infants on the starting platform for longer periods in the discourage condition, infants had more time to vocalize in the discourage condition, and what came out of their mouths was positive–neutral babbles rather than negative whimpers. The ANOVA revealed only main effects for condition, $F(1, 23) = 7.37, p < .05, \eta^2 = .25$; and risk level, $F(1, 46) = 10.99, p < .001, \eta^2 = .33$. As shown in Fig. 6D, negative vocalizations did not depend on mothers' social signals; the ANOVA revealed only a main effect for risk level, $F(1, 46) = 3.72, p < .05, \eta^2 = .15$.

7. General discussion

Traditionally, studies of social-cognitive development and locomotor development are worlds apart, using different methods to address different theoretical issues. The current study brought these two worlds together. We used a locomotor task – walking down slopes in slippery Teflon-soled shoes – to ask whether infants' selective use of social information is dynamically tuned to the current constraints on action. At the same time, we manipulated the social information available to infants – mothers encouraged and discouraged their infants to descend – to disentangle walking experience from walking skill and to examine infants' sensitivity to friction underfoot.

Experiment 1 showed that Teflon-soled shoes severely impair walking skill in experienced 18-month-old walkers: average walking thresholds decreased from 24° while barefoot or wearing standard crepe-soled shoes to 9° in the Teflon-soled shoes. Thus, the normal region of uncertain risk (20°–30°) was displaced to a shallower region of slopes in slippery shoes (<15°). In Experiment 2, 18-month-olds updated their assessment of uncertainty to take their diminished walking skill into account, and they used social information selectively at the shallow region of slopes. These results indicate that adaptive responding depends on walking experience, not walking skill, and that infants are sensitive to the feeling of slip beneath their feet.

7.1. What infant locomotion tells us about social cognition

Uncertainty. Locomotor tasks provide new ways to operationalize and conceptualize uncertainty. The concept of uncertainty is central to studies of social referencing because infants should only seek social information or defer to unsolicited advice when self-generated perceptual information is insufficient (Baldwin & Moses, 1996). When risk is not uncertain (i.e., the situation is clearly safe or impossible), then infants should instead rely on perceptual information from their own exploratory activity. However, in traditional paradigms, the selection of uncertain toys and people relies on researchers' subjective intuitions about what stimuli will seem ambiguous to infants. Moreover, a single bizarre toy or strange person cannot reveal dynamic or precise attunement to the level of uncertainty.

By contrast, uncertainty can be objectively quantified in locomotor tasks across a graded array of risk levels, and infants can be tested in dozens of trials (Adolph, 1997, 2000; Adolph & Avolio, 2000; Adolph et al., 2008; Tamis-LeMonda et al., 2008). In other words, uncertainty can be operationally defined in terms of the probability of walking (or crawling, reaching, etc.) successfully under varying conditions. As demonstrated in the current study, any particular increment of risk (e.g., a single degree of slope) cannot provide the complete picture of infants' assessment of uncertainty. The whole array is needed to reveal whether infants' assessment of risk matches the underlying probabilities in terms of motor skill, and whether infants use social information only at uncertain increments.

Perhaps most important, the current study highlights the dynamic nature of objective uncertainty. Simple manipulations such as varying the slope of the ground surface or the friction at the shoe–floor interface can change the probability of walking successfully. More generally, possibilities for action change with every variation in infants' abilities and in features of the environment. Infants' effective use of social information requires them to track these changes in affordances to guide actions adaptively.

The power of discouragement. A remarkable finding was infants' cautious behavior at 0° slopes when mothers discouraged. Every infant could walk over the flat walkway—they did so multiple times in the warm-up trials. Nonetheless, mothers' discouragement elicited avoidance in half of the infants and increased latency and sliding strategies in the other infants. A similar pattern held across the entire range of shallow slopes: discouraging social signals led to more cautious and conservative responses.

Two mechanisms may underlie the power of discouragement for making infants think twice at the shallowest increments. Possibly, discouragement focused infants' attention on their mothers' face and voice, rather than on the slope. Indeed, some mothers used sharp, abrupt warnings ("Lily, No! Stop!) and stopping guard hand gestures when infants moved forward, followed by calm, soothing, elongated utterances ("Goood, goood, staaay") when infants stopped moving (see Karasik et al., 2008). The overall effect was reminiscent of a dog owner executing the sit–stay command to a pet. A second possibility is that discouragement – coupled with the visual cues for the flat surface or shallow slant – led to increased information gathering by the infants. A consequence of spending a longer period on the starting platform is that infants had more opportunities to gather perceptual information. Indeed, mothers frequently referred to the slope with words and gestures, eliciting looks by infants toward the obstacle. Thus, regardless of whether infants ultimately deferred to their mothers' discouraging advice, mothers may have succeeded in getting infants to look before they leaped.

Fear? A widespread interpretation of infants' avoidance of impossible obstacles (in particular, on the deep side of the visual cliff) is that infants are afraid of falling and that mothers' discouraging messages heighten their natural fear response (Bertenthal & Campos, 1984; Campos et al., 2000; Saarni, Mumme, & Campos, 1998; Sorce et al., 1985). Several lines of evidence, however, argue against a fear-based interpretation of infants' behavioral reactions. In the Sorce et al. (1985) study, for example, infants did not exhibit outward signs of fear. Their affect changed from "happy" to "neutral" when mothers posed joyful versus fearful/angry facial expressions. Similarly, when mothers provided encouraging social messages on the deep side of the visual cliff, neither crossing nor avoidant 9- to 12-month-old infants displayed fearful expressions or accelerated heart rate (Rader, Bausano, & Richards, 1980; Richards & Rader, 1981, 1983). In previous work, 12- and 18-month-olds displayed positive–neutral facial expressions and vocalizations on impossibly steep slopes (Adolph et al., 2008; Tamis-LeMonda et al., 2008). In other words, outward signs of fear do not accompany adaptive motor decisions and negative social expressions do not differ between infants who respond adaptively and those who do not. Saarni, Campos, Camras, and Witherington (2006) argued that infants' smiles and other outward signs of positive affect do not refute a fear-based account because the avoidant behavior itself indicates fear. However, given the circularity of their argument, it is prudent to rely on independent measures of affect beyond avoidance itself.

In the current study, we found no evidence that mothers' discouraging messages or the sight of a precipice instigated fear or any other negative expression. Infants' facial affect did not differ between the encouraging and discouraging conditions; their faces were positive not negative. Positive vocalizations were *higher* in the discouraging condition and negative vocalizations were low in both conditions. Likewise, we found no evidence that steep slopes instigated negative social expressions or that refusals to walk were accompanied by fear. In fact, positive vocalizations *increased* with increasing risk, and negative vocalizations were consistently low across risk levels.

7.2. What infants' use of social information tells us about locomotor development

Infants' selective use of social information at the shallowest increments sheds light on two issues regarding locomotor development. The first issue concerns the effects of locomotor experience (how many days since infants began walking) versus locomotor skill (infants' walking thresholds on slopes). Normally, the two factors are confounded such that novice walkers have little experience in their new upright posture and they also display poor levels of locomotor skill. By dressing infants in Teflon-soled shoes, we transformed experienced, proficient 18-month-old walkers into tippy, poorly skilled walkers, without changing their upright posture or eliminating their months of walking experience.

The 18-month-olds did not respond like the novice 12-month-old walkers in previous work by using social information selectively only at the steepest slopes, and even then with persistently high attempts to walk under impossible conditions (see Fig. 1B). In fact, mothers' social signals had no effect on 18-month-olds' decisions between 30° and 50°, where infants did not budge regardless of their mothers' social message; rather, infants showed the largest effects at the shallowest slopes. The findings lend support to the proposal that it is lack of experience not skill that is responsible for rash responding to potential risk in novice walkers.

A second locomotor issue that is addressed by infants' selective use of social information is their sensitivity to friction underfoot. In previous work where mothers only encouraged infants to descend, 14- and 15-month-olds responded only to slant, not to friction (Adolph et al., 2010). They attempted to walk down the same degrees of slope regardless of whether the condition was high or low friction, and they fell on the low-friction surface on trial after trial. The current study showed that older, more experienced walking infants do display sensitivity to the slip between their feet and the ground surface, as evidenced by the disparity between attempt rates at the shallow slopes under conditions of mothers' encouragement and discouragement. Nonetheless, for the 10°–20° slopes where the probability of success was negligible, attempt rates were relatively high (.33–.77), even in the discouraging condition. Thus, although infants displayed sensitivity to friction that was not revealed in past research that did not manipulate social information, infants' responses were far from adaptive. Apparently, visual information for slant is still a more potent source of information for guiding infant locomotion than tactile information for friction.

7.3. Conclusion

The traditional approach to motor development is overly simplistic. Clearly social information plays a role in guiding locomotion. But, the importance of social information in infants' decisions about action should not be overstated. When infants are presented with conflicting information – social signals from their caregivers versus perceptual information generated by their own exploratory activity – the latter generally wins the day. In no study thus far have infants been found to defer to social information across the board. Such a conclusion is probably good news. In everyday situations, parents cannot be so vigilant that they can protect infants from every potential danger. With the advent of independent locomotion comes increasing autonomy. Although mothers' advice can often be useful, especially under conditions of uncertainty, infants must eventually learn to navigate the world on their own.

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