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What Cruising Infants Understand about Support for Locomotion

Sarah E. Berger
The College of Staten Island and the Graduate Center, The City University of New York

Gladys L. Y. Chan, and Karen E. Adolph
New York University

"Cruising" infants can only walk using external support to augment their balance. We examined cruisers' understanding of support for upright locomotion under four conditions: cruising over a wooden handrail at chest height, a large gap in the handrail, a wobbly unstable handrail, and an ill-positioned low handrail. Infants distinguished among the support properties of the handrails with differential attempts to cruise and handrail-specific forms of haptic exploration and gait modifications. They consistently attempted the wood handrail, rarely attempted the gap, and occasionally attempted the low and wobbly handrails. On the wood and gap handrails, attempt rates matched the probability of cruising successfully, but on the low and wobbly handrails, attempt rates under- and overestimated the probability of success, respectively. Haptic exploration was most frequent and varied on the wobbly handrail, and gait modifications—including previously undocumented "knee cruising"—were most frequent and effective on the low handrail. Results are discussed in terms of developmental changes in the meaning of support.

OBLIGATORY AND SUPPLEMENTAL SUPPORT

At some points in development, children cannot act on their own; external support is obligatory for successful performance of the action. At later

Correspondence should be sent to Karen E. Adolph, Department of Psychology, New York University, 4 Washington Place, Room 410, New York, NY 10004. E-mail: Karen.Adolph@nyu.edu

points in development, external support is supplemental. Children can perform the target skill independently, but external support bolsters existing skills or expands children's abilities to cope with new and challenging situations.

This developmental transition from obligatory to supplemental support is nicely illustrated in the acquisition of upright locomotion. Prior to independent walking, infants can only move in an upright posture with external support to provide the necessary balance: with the help of caregivers holding their arms overhead; using baby walker devices to wheel themselves around; pushing carts, boxes, and chairs while leaning forward; and "cruising" sideways along a coffee table or couch (Adolph, Berger, & Leo, 2011; Frankenburg & Dodds, 1967; Haehl, Vardaxis, & Ulrich, 2000; Karasik, Adolph, Tamis-LeMonda, & Zuckerman, 2012; Karasik, Adolph, Zuckerman, & Tamis-LeMonda, 2013). After the onset of independent walking, external support is no longer needed for basic walking but a caregiver's hand, a bannister, or the wall can augment children's balance for walking along a narrow curb, walking down stairs, or navigating slippery ground. A host of other motor skills follow a similar pattern where caregivers, couch pillows, training wheels, and kickboards provide the necessary postural support before children can sit, ride a bicycle, and swim on their own. Later, the same external supports can expand children's abilities but are no longer obligatory.

EXTERNAL SUPPORT FOR LOCOMOTION

The current study investigated infants' understanding of support at a point in development when support is obligatory for upright locomotion. We asked whether cruising infants distinguish among handrails varying in support properties. Previous work suggests that cruising infants have some understanding that external support is obligatory for upright locomotion: Eleven-month-olds with about 2 months of cruising experience attempted to cruise over an adjustable gap between handrails—analogous to the gaps between couch and coffee table—only if the gap distance was cruisable and well within their arm span (Adolph et al., 2011). Infants gauged the extent of their reach by cruising to the near side of the gap and extending their leading arm toward the far side of the gap. When the gap was too large, they crawled to the other side or refused to go.

Infants' understanding of the utility of external postural support changes over locomotor development. When infants take their first independent walking steps, they no longer require mechanical support for upright stance (Barela, Jeka, & Clark, 1999), but support is still obligatory for upright locomotion because near-walkers lose balance after a step or two. Nonetheless, near-walkers appear bereft of understanding about the necessity of external support for walking: Eleven-month-old near-walkers attempted to walk across impossibly wide gaps between handrails and fell on trial after trial (Adolph et al., 2011). When they attempted to cruise rather than walk, they rarely fell.

After a few months of independent walking experience, infants understand that external support is supplemental, not obligatory. They only use a handrail when it is needed to augment upright balance: Fourteen-month-olds with approximately 3 months of walking experience grabbed vertical support posts to maintain stance on slippery, squishy and narrow surfaces, but not while standing on firm, high-friction ground (Stoffregen, Adolph, Thelen, Gorday, & Sheng, 1997). Even the "quiet touch" of an experienced walker's hand on a stable, horizontal surface—support so minimal that the contact cannot provide mechanical forces for maintaining balance—provides perceptual support for reducing postural sway in upright stance (Chen, Metcalfe, Chang, Jeka, & Clark, 2008; Metcalfe & Clark, 2000; Metcalfe et al., 2005a): Thirteen- to 14-month-olds with at least 1.5 months of walking experience spontaneously applied slight pressure to a handrail before their bodies swayed, suggesting that they used the resulting information prospectively to control standing balance (Barela et al., 1999).

Experienced infant walkers also understand the utility of external support for augmenting upright locomotion: 16-month-olds with approximately 3–4 months of walking experience attempted to walk across narrow bridges only on trials when a handrail was present; they ran straight across wide bridges regardless of whether a handrail was available (Berger & Adolph, 2003). Similarly, visual-haptic exploration of the handrail was limited to trials on narrow bridges; they immediately crossed wide bridges with barely a glance at the handrail and without touching it.

Experienced walking infants can even take advantage of unstable external support to stabilize upright balance. By 6 months of independent walking, quiet touch of an oscillating handrail provided perceptual information for controlling upright stance; infants swayed in tune with the movement of the rail (Metcalfe et al., 2005b). Experienced walkers can also use an unstable handrail for augmenting balance during locomotion. But this requires alternative strategies for coping with the handrail support properties. For example, 16-month-olds with about 4 months of walking experience attempted to cross narrow bridges more frequently when a solid wood handrail was available, compared with a wobbly pliable handrail, but they attempted narrow bridges more frequently with a wobbly handrail than with no external support (Berger & Adolph, 2003; Berger, Adolph, & Lobo, 2005). Infants rarely fell while using wobbly handrails because they limited the amount of weight placed directly on the handrail: They hunched along sideways pressing lightly down on the handrail; they leaned backward and pulled up on the handrail like a mountain climbing rope; they walked sideways and pulled back on the handrail as if windsurfing, and so on.

Similarly, experienced walkers can sometimes take advantage of an ill-positioned handrail. Sixteen-month-olds with 3–4 months of walking experience attempted to cross narrow bridges more frequently if a wood handrail was located at an optimal distance from a narrow bridge—not so close that the handrail pushed their bodies backward over the precipice and not so far that they could not reach the handrail with their feet on the bridge. Infants avoided falling on trials with the too-close handrail by turning sideways and draping their bodies over the rail, but none used the too-far handrail successfully (Berger, Adolph, & Kavookjian, 2010).

CURRENT STUDY

The current study expands on previous investigations into infants' understanding of the utility of external support. We focused on 11-month-olds because at that age most infants have several weeks of cruising experience and can produce multiple trials at a single test session (Adolph et al., 2011; Haehl et al., 2000). Moreover, previous work indicated that 11-month-olds understand that external support for cruising must be within arms' reach (Adolph et al., 2011). But do cruisers also understand that adequate support requires more than a nearby structure to hang onto? In particular, are cruisers, for whom support is obligatory, as savvy as experienced walkers, for whom support is supplemental: Do cruisers recognize that unstable support or an ill-positioned handrail are less optimal than a solid handrail at chest level?

To address these questions, we tested 11-month-old cruisers in four handrail conditions designed to provide varying levels of support: a solid wooden handrail positioned at chest level, two handrail segments interrupted by a large gap, a wobbly deformable handrail, and a low handrail positioned at knee level. Of primary interest was whether infants would distinguish among the various handrails by differential attempts to cruise and whether attempt rates would reflect the probability of cruising successfully. We also asked whether infants would differentially explore the support properties of the handrails to make their decisions and modify their gait patterns to accommodate the support properties of the rail.

Based on previous findings (Adolph et al., 2011), we expected infants in the current study to attempt to cruise over the wood handrail and refuse to cruise over the gap handrail. Previous work provided less indication, however, as to whether infants would attempt to cruise over the wobbly and low handrails, and if they did, whether their attempts would be successful. Prewalking infants exert considerable downward force on a handrail while standing and cruising (Adolph, Vereijken, & Denny, 1998; Barela et al., 1999; Vereijken & Adolph, 1999). Thus, we expected that the wobbly handrail would provide support for locomotion only if infants could stabilize their posture using quiet touch (Chen et al., 2008) or modify their normal cruising style with "hunchback," "mountain climbing," and other such strategies used by experienced walkers (Berger et al., 2005). The low handrail was designed to be too low for cruising comfortably. Thus, we expected that it would provide support for cruising only if infants could coordinate the movements of all four limbs to move sideways (Haehl et al., 2000) while bent from the waist.

Perceptual information about the handrails was available from the starting platform: Infants could see and feel the various handrails before deciding whether to go. In previous work, experienced walking infants explored wobbly and ill-positioned handrails by touching them and extending one arm toward the target handrail (Berger et al., 2005, 2010), and cruisers explored a gap handrail by extending their arm into the gap (Adolph et al., 2011). However, previous work also showed that prewalking infants used a handrail for mechanical support, not for information to control body sway, leading Barela et al. (1999) to speculate that cruisers' use of information from touch is largely reactive, not prospective. Thus, cruisers in the current study might explore handrails but fail to use the information for controlling locomotion adaptively.

Although the handrails could not be adjusted to each infant's body dimensions, we collected measures of body dimensions to verify the approximate positioning of the handrails relative to infants' average body size. Finally, in a series of exploratory correlational analyses, we investigated whether individual differences in infants' attempts, gait modifications, and exploratory activity were related to their cruising experience or body dimensions.

METHOD

Participants

Twenty-five 11-month-olds (± 10 days) participated (nine boys, 16 girls). Data from seven additional infants were lost due to fussiness ($n = 6$) or video equipment failure ($n = 1$). Families were recruited from mailing lists, referrals, and flyers. Most families were white and middle- to upper-income. Infants received a certificate and framed photograph as souvenirs of participation.

As verified in the laboratory, all infants could cruise sideways; 24 also crawled on hands and knees and 1 bum shuffled; none could take independent walking steps. Parents reported infants' cruising experience in a structured interview (Adolph et al., 2011). Cruising experience, counted from the first day infants cruised 1 meter continuously along the edge of a couch or coffee table, ranged from 13 days to 3.39 months (M = 1.70 months). An experimenter measured infants' recumbent height, nude weight, leg length from hip to ankle, and arm span from fingertip to fingertip with the arms outstretched from the shoulders. Height ranged from 70.8 to 79.5 cm (M = 74.5 cm), weight from 7.8 to 12.3 kg (M = 9.6 kg), leg length from 29.2 to 34.8 cm (M = 31.8 cm), and arm span from 69.6 to 81.1 cm (M = 74.5 cm).

Handrails apparatus

Infants were tested on a wooden platform covered with plush carpet (324.5 cm long × 76.0 cm wide × 90.3 cm high). Handrails could be quickly attached to permanent posts along one side of the platform to create the appropriate level of external support for each test condition. In the *wooden* handrail condition (Figure 1a), a solid, wooden handrail (302.0 cm long × 13.5 cm wide) provided continuous stable support for cruising (as in Adolph et al., 2011; Berger & Adolph, 2003; Berger et al., 2010, 2005). The height of the wooden handrail (40.7 cm) was approximately at the infants' chest level, 54.6% of their average height. In the *gap* handrail condition (Figure 1b), wooden starting and landing handrails (105.0 cm long, but otherwise identical to the wooden rail) abutted a 70.5-cm wide gap. The handrail segments were placed too far apart to provide support for cruising, at 94.6% of the infants' average arm span. Adolph et al. (2011) showed that this distance was beyond cruisers' ability. In the *low* handrail condition (Figure 1c), a low wooden handrail (108 cm long × 13.5 cm wide × 16.7 cm high) linked the chest height starting and landing handrails. The low handrail was positioned approximately at knee level so that infants would need to bend over to use it for support, at 22.4% of their average standing height and 52.4% of their average leg length. In the *wobbly* handrail condition (Figure 1d), a foam handrail (108 cm long × 3.5 cm in diameter) connected the starting and landing handrails (as in Berger et al., 2005). If infants rested their full weight on the handrail, it would dip below their knees, and if they leaned into it, it would swing out over the edge of the platform. To equate the wooden handrail with the other test conditions, a middle 108-cm-long

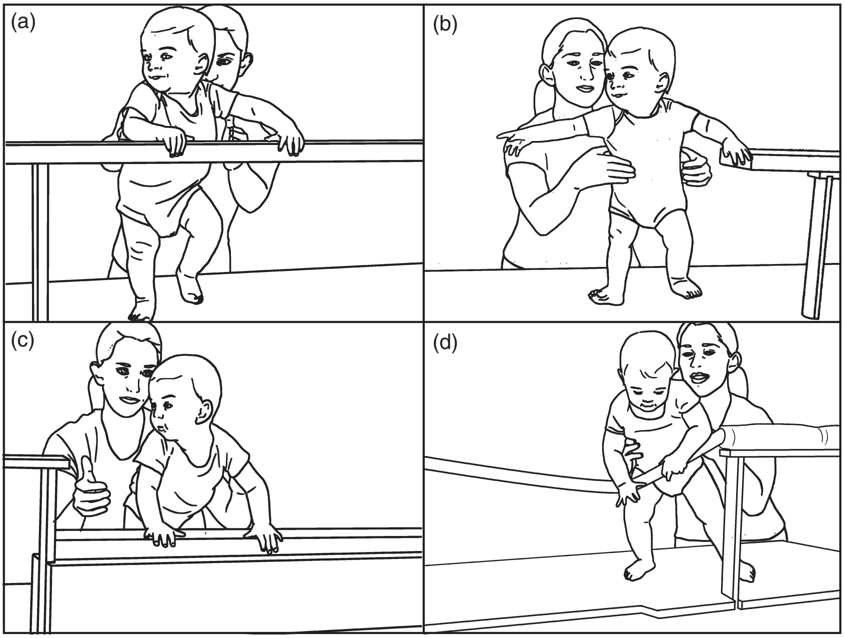

Figure 1 Handrails apparatus. (a) Wooden handrail at chest level. (b) Gap in the handrail. (c) Low handrail at knee level. (d) Wobbly foam handrail. An experimenter (shown) followed alongside infants to ensure their safety; the experimenter kept her hands near infants' torsos but did not touch them (a–c) unless infants began to fall (d). An assistant and the caregiver (not shown) stood at the far side of the walkway and encouraged infants to cross the walkway.

segment was treated as the test area and the surrounding segments as the starting and landing handrails.

Procedure

Prior to testing, all infants demonstrated the ability to cruise the full length of the wooden handrail two times in succession and the ability to crawl the full length of the platform two times in succession. These introductory trials as well as the four test trials on the wooden handrail provided evidence that infants were comfortable moving over the raised platform. Infants also demonstrated the ability to pull to a stand on the handrail, sit back down, and move back and forth between sitting and crawling postures, indicating that infants' decisions about whether to cruise along a handrail were not influenced by a lack of alternative locomotor strategies.

Each infant received a total of 16 trials: each handrail was presented four times, in four trial blocks, each containing the four handrail conditions and ending with a trial on the wooden handrail. Six presentation orders were counterbalanced across sex with four or five infants in each order.

Trials began with the infants in a standing position with both hands on the starting section of the handrail. The experimenter followed alongside infants to ensure their safety; as in previous work (Adolph et al., 2011), the experimenter's hands were near the infant's torso, but not touching the infant unless the baby began to fall (as pictured in Figure 1). An assistant ensured that infants noticed the handrail condition at the start of each trial by holding a toy on the test section of the handrail and then quickly moving the toy to the far end of the landing handrail. When the assistant confirmed that infants had made visual contact with the test section, the experimenter let go of the infants so that they were free to cruise the handrail or crawl to the other side. Caregivers and the assistant stood at the far side of the walkway and encouraged infants to retrieve toys and cheerios. Adults were instructed not to caution infants or tell them whether to cruise, crawl, or avoid going. Trials lasted 45 sec or until infants attempted to cruise the handrail or crawl to the other side, whichever occurred first. Trials were videotaped with side and overhead views mixed onto a single video frame. Sessions lasted approximately 60 min.

Data coding

Data were coded from digital video using Datavyu, a computerized video coding system (Datavyu.org). A primary coder scored 100% of trials. To ensure inter-rater reliability, a second coder scored one to two randomly chosen trials from each handrail condition for each infant (25% of total trials for behaviors on the starting rail and 50% of total trials for gait modifications and exploration mid-rail). Coders agreed on 91–100% of trials for categorical measures, p values for all Cohen's κ coefficients $< .001$. For latency, the correlation between coders' scores was $r(96) = .99$, $p < .01$. Discrepancies were resolved through discussion.

Latency was the time between the beginning of the trial and when infants began cruising or crawling across the test segment of the handrail; on trials when infants avoided going, latency was 45 sec. For each trial, the coder determined whether the infant *attempted* to cruise (placed both hands into the test area while moving upright or cruising on knees) or refused to cruise (crawled or avoided going). On successful attempts, infants cruised safely to the landing handrail segment. On failed attempts, they tried to cruise but fell and required rescue, or they switched from cruising to crawling or sitting mid-rail. On trials when infants crawled, the coder noted whether they pulled to a cruising position on the landing handrail.

For each trial when infants attempted to cruise (whether successful or not), the coder scored seven types of *gait modifications*. A modification was counted if infants took at least one cruising step in the specified position on the test handrail. Within trials, the coder did not score the frequency or sequential order of modifications, only whether each type of modification occurred. Of special interest were the five strategies observed previously in 16-month-olds (Berger et al., 2005, 2010): "hunchback" (body oriented toward the handrail while stooped over from the waist), "mountain climbing" (body oriented toward the landing platform while leaning backward by pulling against the handrail), "windsurfing" (body oriented toward the handrail while leaning backward), "side leaning" (a sort of "drunken" walk with the body oriented toward the landing platform while resting the torso against the rail), and "chest leaning" (body oriented toward the handrail while resting the chest against the handrail). In addition, the coder scored "stretching" (stretching both arms horizontally to full extension) and "knee cruising" (moving on the knees while holding the handrail). Note that it was impossible for infants to demonstrate the hunchback strategy on the wooden handrail because their bodies were too short relative to the rail, and only stretching and knee cruising were possible in the gap condition because there was no handrail in the test area to hang onto or lean on.

For each trial, the coder also noted whether infants engaged in 6 different types of *haptic exploration* of the test handrail: rubbing the hands back and forth along the test handrail, tapping the test handrail, pressing down on the test handrail, pulling up or back on the test handrail, mouthing the test handrail, and extending one arm toward the test handrail or landing handrail. The coder scored haptic exploration at two time points, *prior* to leaving the starting handrail (termed "prior exploration") and *after* embarking onto the test area (termed "mid-rail exploration"). Thus, prior exploration could occur regardless of whether infants attempted to cruise, but mid-rail exploration could only occur on trials when infants attempted to cruise. Coders scored trials as prior exploration when infants touched the test area of the handrail with their leading hand, while keeping their trailing hand on the starting rail. Although the "wobbliness" of the handrail was not immediately visually discernible, infants could gather information about the ability of the rail to support their weight prior to embarking. Coders scored trials as mid-rail exploration when infants touched the test handrail with one or both hands with neither hand on the starting handrail. For both prior and mid-rail exploration, the coder only scored behaviors as haptic exploration if the infant was not cruising while touching (feet stationary for at least 0.5 sec), to ensure that touches were not confused with cruising movements involving the arms. Within trials, the coder did not score the frequency or sequential order of touches, only whether each touch type occurred. Note that in the gap condition, only arm extensions were possible because there was no rail to touch.

RESULTS

Attempts, gait modifications, latency, and haptic exploration were analyzed with repeated measures ANOVAs over the four handrail conditions. Significant effects for handrail condition were followed by paired comparisons with Sidak corrections. Effects of trial order were analyzed with paired *t*-tests by combining the first two trials and the last two trials. We found no effects of sex or condition order, so these factors were excluded from further analyses. The video file from one infant became corrupted partway through data coding, so only data on attempts were available for analyses.

Attempts to cruise

The support properties of the handrail determined whether infants attempted to cruise and whether their attempts were successful. As shown by the total height of the bars in Figure 2a, infants attempted the wooden handrail on nearly every trial ($M = .96$) and attempts dropped precipitously across the other handrail conditions: *M*s = .50 for low, .34 for wobbly, and .10 for gap. Every infant attempted to cruise over the wooden rail, 19 attempted the low, 15 the wobbly, and 6 the gap on at least one trial. The ANOVA confirmed the effect of handrail condition on attempts to cruise, $F(3, 72) = 47.27$, $p < .001$, *partial* $\chi^2 = 0.663$; post hoc tests revealed more attempts on the wood handrail and fewer attempts on the gap handrail than in each of the other conditions (all *p*s < .05), but no difference between attempts on the low and wobbly handrails ($p > .10$). There were no differences in body dimensions (height, weight, arm span, leg length) or cruising experience between the infants who attempted to cruise the low, wobbly, or gap handrails and those who did not, all *p*s > .09.

As shown by the filled areas of the bars in Figure 2a, cruising was possible on the wood and low handrails, but not on the wobbly and gap handrails. Infants cruised successfully on $M = 93\%$ ($SD = 14\%$) and $M = 82\%$ ($SD = 28\%$) of attempts for the wooden and low handrail

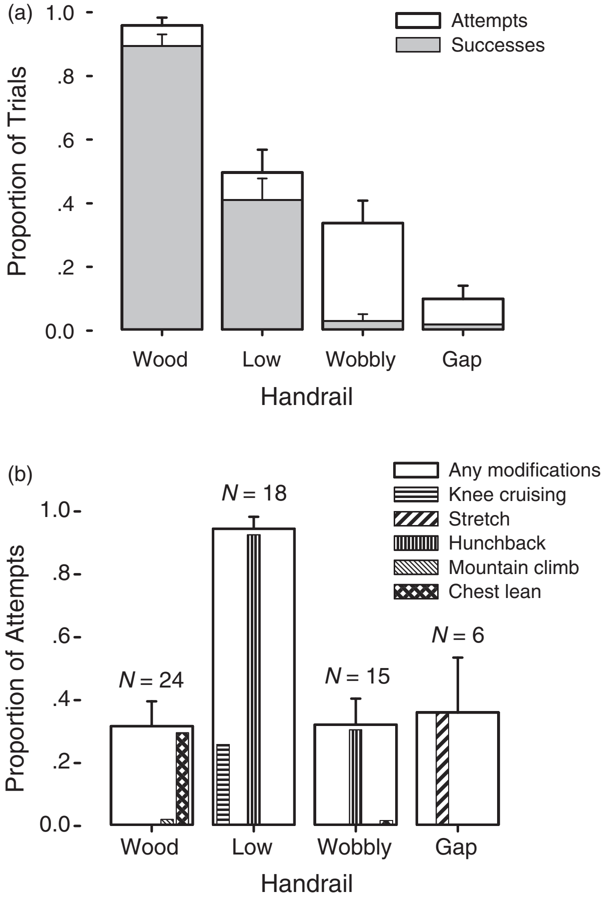

Figure 2 Cruising the handrails. (a) Average proportion of trials infants attempted to cruise each handrail (open bars) and success at cruising on trials that infants attempted (filled bars). Error bars represent standard errors. (b) Average proportion of attempts to cruise that involved gait modifications (open bars) and types of gait modifications (filled bars). Note that infants could display multiple types of gait modifications per trial. Error bars represent standard errors. *N*s denote the number of infants who attempted to cruise. Infants never displayed side leaning and windsurfing, so these gait modifications are not depicted.

conditions, respectively, $t(18) = 1.78$, $p = .09$. Successes were rare in the wobbly (3 of 34 attempts) and gap conditions (2 of 10 attempts). On the three successful wobbly trials, infants took slow, halting steps, stopping repeatedly to regain balance. On the two successful gap trials, the infants inched to the end of the starting handrail and then launched themselves across the gap to catch the landing handrail segment. A few failures were equally dramatic and required rescue by the experimenter. In the wobbly handrail condition, infants swung out over the edge of the walkway hanging onto the wobbly handrail like a trapeze, and in the gap condition, infants stood frozen spread-eagled between handrail segments. However, most failures were relatively tame: Infants cruised partway across the handrail and then shifted from cruising to crawling and made their way to the other end of the platform.

Experience from previous trials in a condition only changed infants' behavior on the wobbly handrail. Infants were equally likely to attempt the wood, low, and gap handrails across trials (all *p*s > .10), but on the wobbly handrail, attempts decreased from the first two trials ($M = .48$, $SD = .43$) to the last two trials ($M = .23$, $SD = .42$), $t(23) = 2.63$, $p < .02$.

Gait modifications

On trials when infants attempted to cruise, gait modifications were relatively common: Overall, infants modified their cruising gait on 47% of attempts, and all infants modified their gait at least once across the 16 trials in the session. Two strategies observed in previous work with 16-month-olds (Berger et al., 2005, 2010)—windsurfing and side leaning—were never displayed by cruisers. However, 20 infants displayed the hunchback strategy, five exhibited chest leaning, three exhibited mountain climbing, and three exhibited stretching. In addition, seven infants exhibited knee cruising, a strategy not reported previously, where infants held the handrail with their hands but cruised on their knees instead of their feet. Figure 2b shows the proportion of attempts that involved gait modifications (note that *N*s reflect the varying number of children attempting to cruise in each condition). The height of the open, surrounding bars shows that gait modifications were most frequent in the low handrail condition (M = 94% of attempts) compared with *M*s = 36, 32 and 32% of attempts for gap, foam, and wood handrails, respectively.

As shown by the filled, internal bars in Figure 2b, the type of gait modification depended on the properties of the handrail. The hunchback strategy was most prevalent on the low (M = 93% of attempts on low) and wobbly handrails (M = 31% of attempts on wobbly); chest leaning was confined primarily to the wood handrail (M = 30% of attempts); stretching was unique to the gap handrail (M = 36% of attempts); and knee cruising was unique to the low handrail (M = 26% of attempts). Note that the sum of the different types of gait modifications could exceed 100% of attempts because infants could use multiple strategies within a single trial. Gait modifications were optional for cruising the wood handrail: Infants succeeded on 64% of attempts without modifying their gait. However, there were no successful trials without gait modifications in the other three conditions. And the frequency of gait modifications did not change over trials within a condition, *p*s > .10.

The number of different types of gait modifications in a condition was related to higher attempt rates for the wobbly and low handrail conditions, $r(13) = .67$ and $r(16) = .52$, respectively, *p*s < .03. Correlations between the number of gait modifications per condition and infants' body dimensions and experience yielded a few significant results: Infants who produced more gait modifications on the wooden handrail tended to have less cruising experience, $r(22) = -.41$, $p < .05$; and infants who produced more gait modifications on the low handrail tended to have smaller stature, $r(14) = -.55$, shorter arm spans, $r(12) = -.59$, and shorter legs, $r(15) = -.61$, all *p*s < .04. In addition, infants who exhibited more knee cruising tended to be lighter than those who did less, $r(16) = -.59$, $p < .01$.

Generally, when infants refused to cruise, they crawled from one end of the walkway to the other (89% of refusal trials) rather than avoid going, and the few avoid trials were distributed evenly across low, wobbly, and gap conditions. Even on refusal trials, infants frequently returned to cruising on the landing handrail. On 45% of the trials where infants left the starting platform in a crawling position, they crawled over the test area to the landing handrail and then pulled to a stand and cruised. Similarly, on 51% of failure trials where infants switched to crawling mid-rail, they crawled to the landing platform and then pulled to a stand on the handrail.

Prior exploration

Latency to leave the starting handrail depended on handrail condition. As shown in Figure 3a, the average latency was approximately 5 sec for the wooden handrail condition and nearly triple that for the other conditions. The ANOVA on latency confirmed the effect for handrail condition, $F(3, 69) = 13.46$, $p < .001$, *partial* $\chi^2 = 0.369$; post hocs revealed differences only between the wooden handrail and the other conditions, *p*s < .05. Latency increased from the first two trials to the last two trials for every handrail type: *M*s wood = 6.32 sec and 8.37 sec (*SD*s = 5.50 and 7.15), $t(23) = -2.10$, $p < .05$; *M*s wobbly = 16.23 sec and 20.44 sec (*SD*s = 11.80 and 12.95), $t(24) = -3.16$, $p < .01$; *M*s low = 16.06 sec and 20.28 sec (*SD*s = 11.34 and 13.02), $t(23) = -2.41$, $p < .03$; *M*s wobbly = 17.60 sec and 21.72 sec (*SD*s = 10.46 and 12.61), $t(24) = -2.41$, $p < .03$. Excluding the subset of trials when infants avoided, they were

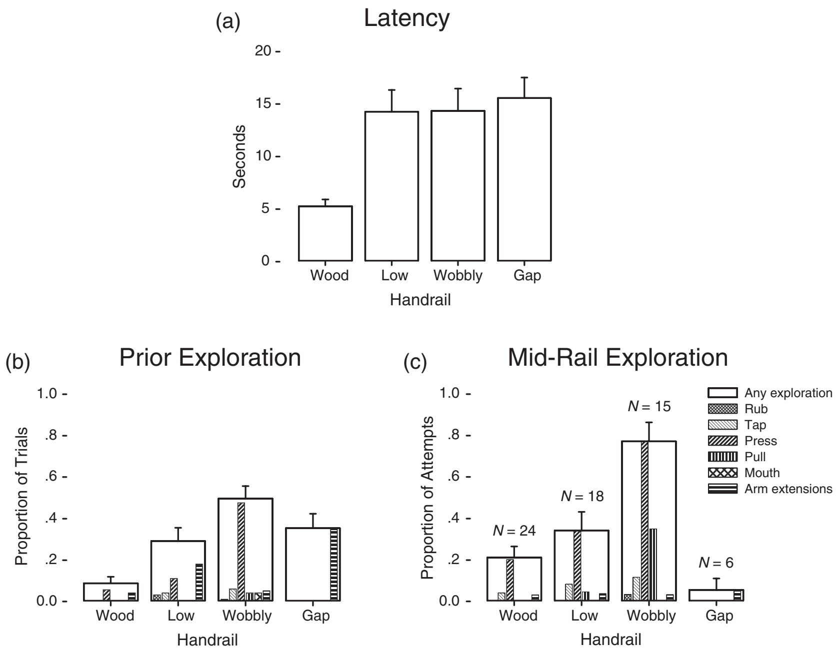

Figure 3 Exploratory behavior. (a) Latency to start onto the handrails. Error bars denote standard errors. (b) Average proportion of trials infants displayed haptic exploration before leaving the starting handrail (open bars) and types of prior exploration (filled bars). Error bars denote standard errors. (c) Average proportion of attempts that involved haptic exploration mid-rail (open bars) and types of mid-rail exploration (filled bars). Note that infants could display multiple types of exploration on each trial. Error bars represent standard errors. *N*s denote the number of infants who attempted to cruise.

faster to leave the starting platform if they cruised (M = 8.02 sec, SD = 3.89) than if they crawled (M = 11.56 sec, SD = 6.14), $t(23) = -3.25$, $p < .01$.

While they hesitated on the starting handrail, infants engaged in haptic exploration of the test handrail. Indeed, trials with haptic exploration prior to embarking had longer latencies (M = 20.41 sec, SD = 10.79 sec) than trials with no haptic exploration, (M = 7.79 sec, SD = 4.82 sec), indicating that infants explored the handrail by touching before deciding whether to cruise, $t(23) = -6.2$, $p < .001$). Every infant engaged in haptic exploration at least once prior to embarking.

As shown by the open bars in Figure 3b, infants engaged in prior haptic exploration in every condition, even in the wooden handrail condition where M = 9% of trials that involved touching. Haptic exploration prior to embarking increased to M = 29 and 35% in the low and gap conditions, respectively, and to M = 50% of trials in the wobbly handrail condition. The ANOVA confirmed the effect for handrail condition, $F(3, 69) = 10.38$, $p < .001$, *partial* $\chi^2 = 0.311$; post hoc comparisons revealed more prior haptic exploration on the wobbly handrail compared with wood and in the gap handrail condition compared with wood, ps < .002. Prior exploration decreased from the first two trials to the last two trials for the wood and wobbly handrails: Ms wood = .17 and .01 (SDs = .28 and .07), $t(23) = 3.05$, $p < .01$; Ms wobbly = .65 and .39 (SDs = .41 and .37), $t(22) = 2.58$, $p < .02$.

Not only did the wobbly handrail elicit more haptic exploration before starting onto the handrail, but also the types of exploration were most varied (filled, internal bars in Figure 3b). Across infants, we observed six different types of haptic exploration prior to starting onto the wobbly handrail, four types before starting onto the low handrail, 2 for wood, and 1 for gap (where only arm extensions were possible). Similarly, individual infants also showed more diversity in prior haptic exploration on the wobbly handrail (M = 1.75 types, SD = 1.19) than on the low (M = 1.00, SD = 1.02), gap (M = 0.67, SD = 0.48), or wooden handrails (M = 0.33, SD = 0.56). An ANOVA confirmed differences between handrails, $F(3, 69) = 12.67$, $p < .001$, *partial* $\chi^2 = 0.355$, and post hocs showed more diversity in exploration on the wobbly handrail than the wood or gap handrails, ps < .001. Across handrail conditions, pressing and arm extensions were the most common forms of exploration prior to embarking. Within conditions, pressing (M = 48% of trials) and pulling (M = 12% of trials) were most frequent on the wobbly handrail; arm extensions were most frequent on the gap (M = 35% of trials) and low handrails (M = 18% of trials); rubbing and tapping occurred only on the wobbly (Ms = 1 and 6%, respectively) and low handrails (Ms = 3 and 4%, respectively), and mouthing (M = 4% of trials) was rare and limited to the wobbly handrail.

Mid-rail exploration

After starting onto the test handrail, infants frequently stopped cruising and engaged in further haptic exploration while standing in one place; 21 infants engaged in mid-rail exploration at least once. Exploration prior to leaving the starting handrail and mid-rail exploration was correlated for the wood and wobbly conditions, $r(22) = .84$ and $r(13) = .55$, respectively, ps < .04. Figure 3c shows the proportion of attempts when infants explored mid-rail (note Ns denote the varying number of infants who attempted to cruise.) The wobbly handrail elicited more trials involving mid-rail exploration (M = 77% of attempts) compared with the low (M = 34% of attempts), wood (M = 21% of attempts), and gap handrails (M = 6% of attempts), and mid-rail exploration was more varied on the wobbly handrail than on any of the others. Infants stopped cruising partway across the wobbly rail to press it down (M = 77%) and pull it up (M = 35%) in bouts of apparent delight; they also tapped it (M = 12%), rubbed it (M = 3%), and extended their arms (M = 3%). Exploration, especially pressing down on the test handrail (M = 20% of attempts), became more frequent on the wooden handrail after embarking compared with before embarking (compare Figures 3b,c), but the pressing and other behaviors had a different, more sober quality compared with the wobbly rail. Infants also exhibited more trials of pressing (M = 34% of attempts) on the low handrail after embarking compared with before embarking, perhaps because prior to embarking it was difficult to lean down to press the low rail while keeping the other hand on the starting handrail. Mid-rail exploration did not change over trials within a condition. Greater diversity in mid-rail exploration was related to higher attempt rates on the wobbly handrail, $r(13) = .89$, $p < .001$. Individual differences in infants' exploratory activity were not related to their body dimensions or cruising experience, all ps > .10.

DISCUSSION

We encouraged prewalking 11-month-olds to cruise over handrails that provided varying levels of support. Infants tailored their attempts to cruise, latency to go, haptic exploration, and gait modifications to the support properties of the handrails. But what do cruisers really understand about external support for upright locomotion? Is their understanding equivalent to that of experienced walkers?

Cruising infants' understanding of support

Moving by cruising is compelling for infants. Although infants could crawl, infants cruised on nearly every trial on the wood handrail. In the other handrail conditions when infants fell or crawled rather than cruised, they frequently pulled themselves to a cruising posture on the landing platform. Latency increased across trials in every condition, including the wood handrail, suggesting that infants grew tired over the course of the session. But it did not make them more reluctant to cruise: Infants were faster to leave the starting handrail if they cruised than if they crawled. Thus, we have assurance that infants' refusals to cruise reflected negative appraisal of the support properties of the handrail, not a general reluctance to cruise or apprehension about moving over the raised walkway.

The primary outcome measure was infants' attempt rates. On one reading of the data, cruisers have impressive understanding of external support for locomotion. They attempted to cruise over the wood handrail on nearly every trial, they rarely attempted to cruise the gap handrail, and they attempted the wobbly and low handrails on an intermediate proportion of trials. These findings suggest that cruisers relied on spatial information about handrail distance and position, as well as haptic and proprioceptive information about the stability of the support surface when deciding that too-far, unstable, and ill-positioned handrails were less optimal than a solid wood handrail at chest height. Moreover, as in previous work (Adolph et al., 2011), attempts on the wood and gap handrails correctly reflected the probability of cruising successfully.

However, on another reading of the data, cruisers lack important insights into the nature of obligatory external support. In contrast to experienced walkers whose attempt rates matched the probability of walking successfully on wobbly and ill-positioned handrails, cruisers' attempt rates on the wobbly and low handrails did not reflect the probability of cruising successfully. On trials when infants attempted to cruise, they were equally unsuccessful on the wobbly and gap handrails and equally successful on the low and wood handrails. So why were attempt rates higher on the wobbly handrail relative to the gap and why were attempt rates lower on the low handrail relative to wood?

For the wobbly handrail, 15 infants attempted to cruise at least once and fell. However, attempt rates on the wobbly handrail decreased over trials, suggesting that infants did not initially recognize that cruising was impossible, but learned about affordances for locomotion on a deformable surface from falling on previous trials (Joh & Adolph, 2006). This pattern contrasts with findings from 16-month-old walkers whose attempts rates increased over trials and for whom walking was possible with a wobbly handrail (Berger et al., 2005). Perhaps for cruisers, the sight and feel of a handrail at chest height were sufficiently compelling to elicit attempts to cruise, at least on the first encounters. Or perhaps as Barela et al. (1999) suggested, cruisers cannot use information from touch to control posture prospectively. Alternatively, infants may have perceived that the wobbly handrail could not support their weight, but cruised nonetheless because they were initially drawn to the novel affordances of a deformable support surface. Infants engaged in more frequent and varied haptic exploration of the wobbly handrail compared with the other handrails prior to leaving the starting handrail and also mid-rail. The video recordings were striking in infants' engagement and delight in exploring the wobbly rail. However, prior exploration decreased over trials, suggesting that the allure of the wobbly rail may have worn thin after an encounter or two.

For the low handrail, some infants may not have realized that cruising was possible; 6 infants never attempted to cruise the low handrail. For the 19 infants who did attempt to cruise the low handrail, they always modified their gait by hunching over or knee cruising. Moreover, attempt rates and gait modifications did not change over trials, suggesting that infants discovered alternative strategies on their first attempt. Possibly, the cost of cruising in a stooped-over posture or cruising on their knees was too high and so infants opted to crawl on half of the low handrail trials rather than to cruise.

The knee cruising strategy was unexpected. We know of no prior report that infants can cruise or walk on their knees. Knee cruising was especially striking because infants continued to use the low handrail for manual support while moving on their knees instead of their feet. Knee cruising was a creative way of lowering their center of gravity so as to remain stable and effectively use the low handrail for support. Frequency of knee cruising on the low handrail was negatively correlated with body weight, and overall frequency of gait modifications on the low handrail was negatively correlated with height, arm span, and leg length. Perhaps being smaller made it easier for infants to use the low handrail in hunchback and knee cruising positions because smaller infants could more easily distribute downward forces on the rail. However, for most analyses, cruising experience and body dimensions were unrelated to individual differences in infants' performance. Future work using a longitudinal design might be more effective in identifying the developmental factors that underlie individual differences.

Gait modifications were highly specific to the support properties of the handrails (Figure 2b). Alternative strategies were ineffective on the wobbly and gap handrails and unnecessary on the wood handrail. Cruisers never displayed some strategies used effectively by older walkers, and infants never cruised on their knees on the wobbly handrail where this strategy might have proven effective. A generous interpretation of these findings is that infants deliberately geared their gait modifications to the constraints of each handrail. A more conservative interpretation is that cruisers' gait modifications emerged more serendipitously en route. For example, infants may have used the hunchback strategy on the wobbly handrail because it dipped down when they attempted to cruise normally, the stretch strategy on the gap handrail because they started cruising and got caught short, and the chest leaning strategy on the wood handrail because they were tired. Indeed, frequency of gait modifications on wood was negatively correlated with cruising experience.

Similarly, haptic exploration was highly specific to handrail type (Figure 3). The wood handrail elicited shorter latencies than the other handrail conditions, and the wobbly handrail elicited more frequent and varied prior exploration relative to the other handrails. Specific behaviors such as pressing, pulling, and arm extensions were also handrail specific. One possibility is that differential exploratory activity reflects an intentional effort to generate information about whether to cruise. For example, infants may have pressed the wobbly handrail to generate information about whether it would support their weight and extended their arms toward the low and gap handrails to generate information about reachability. An alternative possibility is that differential exploration emerged because of the handrail characteristics and the novelty of the conditions. In support of this possibility, infants also engaged in spontaneous haptic exploration mid-rail. In fact, their vigorous exploration of the wobbly handrail—pressing down and pulling up—often upset their upright balance, suggesting that exploration of the novel elastic properties trumped information-gathering in the service of locomotion. Regardless of intent, prior exploration could have provided information about the suitability of the handrail for cruising. But initially, on the wobbly handrail, it did not. Both prior exploration and attempt rates were higher on the first two trials on the wobbly handrail than on the last two trials, suggesting that cruisers may have difficulty using information from touch for controlling balance prospectively (Barela et al., 1999).

Obligatory vs. supplemental support

A hallmark of motor development is the transition from obligatory reliance on external support for performing basic skills to exploiting external support for supplementing and expanding basic skills. A caregiver's hand, for example, is necessary for upright locomotion at an earlier point in development and supplemental at a later point. The function of hand holding changes although the outward appearance of the behavior looks similar.

What develops with the changing nature of support? One set of developments involves infants' growing capacities for upright balance and locomotion. Historically, researchers have focused on the developmental progression under standard conditions: pulling to a stand against furniture, maintaining upright stance, cruising, walking, and stair climbing and descent (Atun-Einy, Berger, & Scher, 2012; Barela et al., 1999; Berger, Theuring, & Adolph, 2007; Frankenburg & Dodds, 1967; Haehl et al., 2000; Karasik et al., 2013; Vereijken & Adolph, 1999; Vereijken & Albers, 1998 April; Vereijken & Waardenburg, 1996 April). The current study adds to the recent literature on developmental changes in infants' capacities for upright stance and locomotion under varying conditions of external support by showing that cruisers, such as experienced walkers, are capable of modifying their gait to accommodate specific support properties (e.g., Adolph et al., 2011; Berger et al., 2005, 2010; Metcalfe et al., 2005b). In particular, cruisers are capable of cruising on their knees.

A second set of developments involves infants' recognition that external supports can provide new possibilities for stance and locomotion. At the pull-to-stand phase, infants sometimes pull up and sit down over and over, as if testing the new actions afforded by the external support. The transition to cruising must entail a sort of revelation that the same support for standing in one place will also provide support for moving the body to a new location. Prewalking infants commonly signal parents that they want to walk with caregivers holding their hands (Karasik et al., 2013), and findings from previous work (Adolph et al., 2011) and the current study indicate that by the time they are cruisers, infants recognize not merely that nearby support is obligatory for upright locomotion, but also that they must attend to the functional properties of that support. By the time that experienced walkers use handrails to augment their balance, they have recognized that external supports such as handrails, bannisters, and caregivers' hands can function as tools for expanding affordances for upright locomotion.

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