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Object interaction and walking: Integration of old and new skills in infant development

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Abstract

Manual skills such as reaching, grasping, and exploring objects appear months earlier in infancy than locomotor skills such as walking. To what extent do infants incorporate an old skill (manual actions on objects) into the development of a new skill (walking)? We video recorded 64 sessions of infants during free play in a laboratory playroom. Infants' age (12.7–19.5 months), walking experience (0.5–10.3 months), and walking proficiency (speed, step length, etc.) varied widely. We found that the earlier developing skills of holding and exploring objects are immediately incorporated into the later developing skill of walking. Although holding incurred a reliable cost to infants' gait patterns, holding and exploring objects in hand were relatively common activities, and did not change with development. Moreover, holding objects was equally common in standing and walking. However, infants did not interact with objects indiscriminately: Object exploration was more frequent while standing than walking, and infants selectively chose lighter objects to carry and explore. Findings suggest that the earlier appearance of some skills may serve to motivate and enrich later appearing skills.

Skill acquisition in infancy is remarkable for its tremendous rapidity, diversity, and scope of accomplishment. Over the course of their first two years, infants acquire a host of new skills —walking, talking, interacting with objects and people, and so on. Each skill progresses from a clumsy first approximation to functional competence, and different skills emerge at different times. What happens as infants achieve mastery in one domain while simultaneously trying to acquire a new skill in another domain? To what extent do infants incorporate existing skills into actions supported by newly emerging skills?

How Are Old Skills Incorporated into New Skills?

On one extreme, infants could suppress already-mastered skills and wait to use them until the later-appearing skills improve (Berger, 2004; Berger, Cunsolo, Ali, & Iverson, 2017; Bloom & Tinker, 2001). That is, infants might temporarily ignore an already mastered skill

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to focus their attention and energy on acquiring a new one. In real time, performance of the old skill would decrease to allot resources to practicing the new skill. As the new skill is solidified over development, both skills could then be performed with ease in real time. For example, in the moments around speaking, newly talking infants decrease emotional expressions to concentrate their efforts on forming words, whereas experienced infant talkers can easily speak while simultaneously emoting (Bloom & Capatides, 1987). However, a few months later when experienced infant talkers build constructions during object play, they reduce their speech and emotional expressions to focus attention on object construction (Bloom & Tinker, 2001). Similarly, in the motor domain, challenging tasks for new walkers tap infants' limited cognitive resources resulting in failures of motor planning and inhibition (Berger, 2004, 2010; Boudreau & Bushnell, 2000).

On the other extreme, infants could immediately incorporate earlier appearing skills into the later appearing skills (Bruner, 1973; Gibson, 1988). Execution of the newer skill would substantially lag behind execution of the older skill, and could even initially disrupt performance. But skills such as walking, talking, and object interaction will ultimately need to be integrated. Thus, it may be beneficial for infants to practice old and new skills together from the beginning, rather than performing each skill in isolation. And improvements in new skills may in turn facilitate improvements in the old skills. For example, reaching, grasping, and object exploration become incorporated nearly immediately into a more upright posture as infants learn to sit independently; sitting, in turn, facilitates improvements in reaching and visual-manual object exploration (Harbourne, Lobo, Karst, & Galloway, 2013; Rachwani, Santamaria, Saavedra, & Woollacott, 2015; Rachwani et al., 2013; Soska & Adolph, 2014; Soska, Adolph, & Johnson, 2010).

However, the extent to which infants incorporate old skills into newly emerging skills likely vacillates between the two extremes, or lies somewhere in the middle. Moreover, the real-time integration of old and new skills likely begins during spontaneous play, when infants select for themselves which actions to perform (Bruner, 1973). Although emoting temporarily takes a back seat to speaking during free play, the evidence for immediate integration of reaching and sitting—and other earlier and later appearing perceptual-motor skills—is limited to experimentally controlled laboratory tasks. Possibly, during natural activity, infants choose to suppress manual actions to focus on sitting, just as they suppress emotion to focus on language during free play (Bloom & Tinker, 2001).

Here, we examined real-time and developmental relations between two fundamental but diverse infant skills—manual actions on objects, which begin at 3 to 5 months of age, and walking, which emerges between 11 and 16 months. During the interim, reaching, grasping, and object exploration become increasingly sophisticated and refined (Adolph & Robinson, 2015; Smitsman & Corbetta, 2010). The advent of independent mobility—crawling, cruising, and walking—provides infants with access to objects beyond their immediate reach (Gibson & Schmuckler, 1989). But when and how do infants perform concurrent manual actions on objects—holding and exploring objects—while walking? At some point, both manual and locomotor actions become so adroit and integrated that carrying small objects becomes trivial to adults, but how do we get there from the initial parade of infant skills? Is it even possible for a walking infant to simultaneously engage in visual or manual exploration of an object in hand?

The extent to which infants incorporate old skills into new ones should depend on the costs and benefits of doing so, and on infants' ability to mitigate those costs. If incorporating an old skill into a newly emerging skill comes with little cost or provides notable benefits, then immediate integration of the two skills would be reasonable. Likewise, if infants can easily mitigate the costs of integration, there is little reason to suppress older, well-practiced skills. If, however, incorporating the old skill disrupts activity and imposes a cost that infants cannot mitigate, infants might be best served by focusing their attention on the new skill to be learned, integrating it with pre-existing skills only after it is mastered.

Costs of Object Interaction in the Development of Walking

At first blush, object transport has clear costs. For new walkers, the mere act of staying upright is difficult (Ivanenko, Dominici, & Lacquaniti, 2007); new walkers average 32 falls/hour during free play (Adolph et al., 2012). Based on biomechanical principles, carrying objects should exacerbate the already thorny problem of balance control (Shumway-Cook & Woollacott, 2017), and walking while manually exploring objects in hand should require more attention and effort than walking with hands free. Indeed, when infants walk back and forth in standard laboratory tasks with heavy loads (~15% body weight) strapped to their bodies, they display less mature gait patterns and more falls, and new walkers are more adversely affected than more experienced walkers (Garciaguirre, Adolph, & Shrout, 2007; Vereijken, Pedersen, & Storksen, 2009). While traipsing back and forth carrying even lightweight objects in their hands, infants hold their arms in awkward positions, and interlimb coordination is altered (Hsu, Miranda, Chistolini, & Goldfield, 2016; Mangalindan, Schmuckler, & Li, 2014). These data indicate that carrying objects—especially heavy ones—incurs a cost on walking and the cost lessens as walking improves. Given these conditions, infants might reasonably choose to temporarily suppress object interaction while walking to focus attention on the new locomotor skill, and integrate the two only after walking has sufficiently improved.

Despite potential costs, while playing freely in their homes, new walkers spontaneously choose to carry objects at high rates—43 times per hour, on average—and often with no apparent goal other than the delight of transporting objects (Gibson, 1988; Karasik, Adolph, Tamis-LeMonda, & Zuckerman, 2012; Karasik, Tamis-LeMonda, & Adolph, 2011, 2014). Previous work reported that spontaneous carrying increases with walking experience, which suggests that infants may wait until walking improves to integrate it with manual actions. However, the frequency of carrying was not normalized by the frequency of walking (Karasik et al., 2012). Thus, effects of walking experience on carrying may have been driven by the greater frequency of spontaneous walking in more experienced walkers (Adolph et al., 2012). Previous work also reported that new walkers fall less—not more—frequently while spontaneously carrying objects than while walking with hands free, suggesting that immediate integration of the two skills is beneficial to infants (Karasik et al., 2012). But, as with carrying, fall rates were not normalized by the frequency of walking. Higher rates of walking without objects rather than with objects in hand may explain the apparent benefits of carrying objects.

Nonetheless, sophisticated measures of postural sway show that standing balance is improved—not impaired—when infants are encouraged to hold and explore small objects in their hands, further suggesting that immediate integration of object skills into walking may be beneficial to infants (Claxton, Haddad, Ponto, Ryu, & Newcomer, 2013; Claxton, Melzer, Ryu, & Haddad, 2012). And standing infants, like adults, show less postural sway while engaged in a visual exploration task (Claxton, in press; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). Thus, normalized fall rates and more sensitive measures of walking may reveal benefits of holding and exploring objects on walking, which would suggest that infants might be best served by immediately integrating the new skill of walking with the older skill of object manipulation. However, exploration while walking has not been investigated, and such dual tasking may not be possible for infants.

Even if incorporating object interactions into locomotion comes with a cost, infants could mitigate the cost in several ways. They could select only small, lightweight objects that pose less threat to their developing balance. They could hold objects in ways that don't interfere with walking, for example, holding small objects in one hand held at the side, rather than two hands in front of the body. And they could perform harder actions—interacting with larger, heavier, objects or performing more sophisticated manual actions—while standing rather than while walking.

Previous work shows that infants' object interactions differ based on object properties. For example, infants bang rigid objects more than soft ones, scratch textured objects more than smooth ones, mouth rubber objects more than furry ones, and wave light objects more than heavy ones (Bourgeois, Khawar, Neal, & Lockman, 2005; Lobo, Kokkoni, de Campos, & Galloway, 2014; Palmer, 1989; Ruff, 1984). Likewise, infants tailor their grasping strategies to objects of different sizes and shapes (Lee, Liu, & Newell, 2006), contacting small objects with one hand and larger objects with both hands (Palmer, 1989). Thus, infants are capable of adjusting their manual actions to the specific properties of objects when tested only in the manual domain. However, to date, no work has asked whether they are also able to tailor their actions in the manual domain to account for the locomotor domain. We do not know whether infants would choose to interact with objects selectively to mitigate the effects on walking, to suppress manual skills entirely while walking, or to simply perform both skills at once and accept whatever costs might arise. Likewise, past work has not looked at how infants spontaneously interact with objects of different properties—that is, how they choose to interact with objects in a naturalistic setting, where they themselves chose which objects to play with.

Although holding and exploring objects is likely more difficult while walking than while standing, these two postures have not been compared directly in either structured laboratory tasks or during spontaneous free play with objects. More generally, evidence of selectivity in concurrent object interaction and walking is limited due to study designs. In structured laboratory tasks, infants' only option is to obstinately refuse to walk, and they do so more frequently for heavy loads than for light ones (Bushnell, Baxter, Fitzgerald, & Clearfield, 2009; Vereijken et al., 2009). During natural activity in their homes, infants spontaneously select small objects to carry more frequently than large ones (Karasik et al., 2012). Although object weight is also a critical factor for selecting objects to carry, weight cannot be easily estimated from video recordings for the variety of found objects spontaneously carried around infants' homes, so this measure was not analyzed in previous work.

Current Study

Our overall goal was to understand developmental changes in the real-time relations between walking and manual actions on objects as infants become more experienced, proficient walkers. In particular, we aimed to determine the extent to which newly walking infants spontaneously incorporate manual actions into the developing skill of walking during free play, and how incorporating old skills into new ones changes with age and walking experience. At one extreme, infants could temporarily relegate object interaction to times when they are stationary so as to focus all their efforts on walking. At the other extreme, infants could immediately and over the longer term incorporate object interaction into walking by transporting and exploring objects while on the move. Finally, we asked what cost integrating the new and old skills entails, and whether infants are capable of mitigating those costs.

Infants played freely with their caregivers in a large laboratory playroom furnished with several toys varying in weight, size, and function. We compared the quantity of spontaneous walking while concurrently holding and exploring objects versus walking without objects in hand. Previous work indicates that merely holding objects can disrupt walking due to biomechanical factors (Garciaguirre et al., 2007; Hsu et al., 2016; Mangalindan et al., 2014; Vereijken et al., 2009). But effects of exploring objects while walking are unknown. Exploration could improve walking as it does for standing, perhaps by leading infants to walk more carefully (Claxton et al., 2013; Claxton et al., 2012) or disrupt walking, perhaps by diverting infants' attention away from walking.

To understand the effects of development, we tested infants across a wide range of age, walking experience, and walking proficiency. Presumably, older infants have more available resources for attention and effort; more experienced walkers have more practice carrying and exploring objects while walking; and more proficient walkers should be less affected by the biomechanical consequences of concurrent object interaction. We measured walking proficiency in a standard gait task: Infants walked several times in a straight path to their caregivers over a pressure-sensitive mat, and we calculated their walking speed, step length, and step width (Adolph & Robinson, 2013, 2015; D. K. Lee, Cole, Golenia, & Adolph, 2018). Of course, age, experience, and proficiency are intercorrelated such that older infants are also more experienced and proficient, providing a way to corroborate parents' reports of walking experience and measures of walking proficiency (Adolph, Vereijken, & Shrout, 2003).

The playroom was equipped with video cameras and the floor was covered with a large, pressure sensitive mat. We assessed costs and benefits by comparing normalized fall rates and the maturity of gait patterns as infants spontaneously walked with and without objects in hand over the mat in the course of free play. Previous work validated “natural” measures of gait via robust correlations with gait measures in the standard straight-path task and with expected improvements in natural gait patterns over weeks of walking experience (D. K. Lee et al., 2018). We assessed the selectivity of infants’ actions on objects by asking whether object interactions were more frequent while standing compared with walking, whether infants selected lighter objects for transport, and whether they employed uni- and bimanual strategies based on object weight.

Method

Participants

The final dataset included observations of 51 infants (25 boys, 26 girls) between 12.69 and 19.53 months of age. The dataset included a mix of cross-sectional and longitudinal data: 40 infants were tested once, 9 were tested twice and 2 were tested three times, for a total of 64 sessions. All infants were from the New York City area, healthy, and born at term. The study was conducted according to guidelines laid out in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at the New York University. Parents reported children’s race as white (65%), Asian (4%), black (4%), multiple races (21%), or chose not to respond (6%); 18% were Hispanic, and 4% chose not to respond. In a structured interview, parents reported the first day they saw their infants walk 3 meters across a room without stopping, falling, or holding onto anything for support; onset dates were confirmed with home videos, photos, and calendars/baby books if available (Adolph et al., 2003). Infants’ walking experience (time between test date and walk onset date) ranged from 0.46 to 10.26 months ($M = 4.21$ months). Three additional infants (14.50–18.70 months of age, 0.23–4.93 months of walking experience) only held objects in 1–4 bouts of standing and walking, so their data were excluded from the final sample. Video excerpts, raw videos, and demographic data are shared on the Databrary digital library (databrary.org; https://nyu.databrary.org/volume/89; https://nyu.databrary.org/volume/459).

Playroom, Objects, Instrumented Mat, and Procedure

Infants played freely with their caregiver for 20 minutes in a large laboratory playroom (5.97 m × 9.42 m) with a couch, padded pedestal, raised platform, small slide, carpeted stairs, and wooden stairs. Caregivers were told to interact normally with their baby and to mind the infant’s safety. In every session, 6 toys were placed in set locations around the room: toy car with detachable door and roof, rattle ball, plush dog, jingling apple, musical saxophone with song buttons, and “crocodile” xylophone. Because infants often detached the car roof when they played with the car, 7 objects were effectively available (see colored bars in Figure 1A). We chose these objects based on their functionality: The car and dog are imaginative toys; the ball and apple make noise when shaken; and the saxophone and xylophone are musical instruments that make noise when pressing buttons.

In addition, most infants found additional objects for holding and transport (e.g. book, mother’s cell phone, baby’s sock), which were not available in every session (see gray bars in Figure 1A). The "found" objects were taken from toy shelves in the playroom or were common objects, so we could measure their weight. Thus, objects varied in weight (e.g., 20 g for the car door, 830 g for the xylophone), size (tiny car door vs. large xylophone), shape (round apple vs. oblong xylophone), functionality (buttons on saxophone turned on music, rattle ball made noise when shaken), and ease of handling (squishy plush dog vs. rigid xylophone). With the exception of the stuffed dog—which was light for its size—larger objects (based on length × width × height) were heavier, $r(4) = .94$, $p < .001$. Because past work showed clear effects of increasing weight on infants' developing balance, we categorized objects into three weight categories based on the distribution of weight: light (<150g and <1.4% of infants' average body weight), medium (150g - 700g; between 1.4% and 6.6% of body weight), and heavy (>700 g; more than 6.6% of body weight). Note, none of the objects were as heavy as the loads strapped to infants' bodies in previous work (Garciaguirre et al., 2007; Vereijken et al., 2009) but all were in the range of weights that affected arm movements while walking with objects in hand (Hsu et al., 2016; Mangalindan et al., 2014).

In 60 of the 64 sessions, infants' walking proficiency was measured in a standard straight-path task as they walked over a Protokinetics pressure-sensitive mat (data were missing from 4 sessions due to experimenter error or equipment failure). The experimenter stood infants on one end of the mat and encouraged them to walk straight to their caregiver who lured them from the other end with toys and snacks. Due to the availability of a larger mat (about 1/3 of the room) in the last 32 sessions, we also collected "natural gait" data as infants spontaneously walked on the mat during free play (Lee et al., 2018). Although infants walked on the mat at least once in all 32 sessions, they did so *both with and without* holding a toy in only 24 sessions because most bouts of spontaneous walking did not occur on the portion of the floor that was instrumented.

A camera with fish-eye lens affixed to the ceiling recorded a full-room view, and two additional fixed cameras recorded infants' activities on the pressure-sensitive mat. During free play, an experimenter recorded a closer view of infants' activities using a hand-held video camera. The experimenter was not intrusive and did not interact with infants or caregivers. The four camera views were synced for later video coding.

Video Coding

A primary coder scored videos of the free play sessions using Datavyu (datavyu.org), a free video-coding tool that allows frame-by-frame analysis for user-defined event durations and categorical codes. To determine whether infants were interested in the toys we made available, the coder scored the duration of each *manual interaction* with the 7 standard toys, regardless of whether infants were in upright, sitting, or prone postures, or played with the toy while holding it or while resting it on a surface. As in Cole et al. (2016) and Lee et al. (2018), the coder identified the duration of each *walking bout* (time between the first step, when a foot lifted from the floor, and the last step, when a foot rested on the floor for at least 0.5 s and infants were not shifting weight to another upright step), *number of steps* per bout, duration of each *standing bout* (both feet on the floor for at least 0.5s, not fully supported by furniture or caregiver, legs extended), and *falls* while walking (falls while climbing and other activities were excluded). Periods when infants were upright but holding their caregiver’s hand or holding a support surface were excluded.

Then, for each walking and standing bout, the coder scored whether infants *held an object* (object in infants’ hands and not resting on a support surface), *explored the held object* manually (mouthing, shaking, hitting, banging, swinging, rotating, pressing buttons and poking fingers into holes, fingering, stroking) and/or with visual inspection, which object was held (including found objects), and whether the object was held *uni- or bimanually* (in one or both hands). The coder noted whether the object was held for the entire bout or if discarded, whether it was *thrown*, *placed*, or *dropped*.

A second coder scored 25% (randomly selected) of each infant’s data for each variable to ensure that the codes were reliable. Inter-observer agreement was high: 95.4–99.9% exact agreement for categorical codes (kappas ranged from 0.84–1.00, all ps < .001), and rs > .99 for durations and number of steps per walking bout.

Processing of Gait Measures

We processed the 60 sessions with standard gait data as in previous work (Bisi, Riva, & Stagni, 2014; Bisi & Stagni, 2015; Ivanenko, Dominici, Cappellini, & Lacquaniti, 2005; D. K. Lee et al., 2018; Van de Walle et al., 2010; Yaguramaki & Kimura, 2002): We removed 1–3 steps from the beginning and end of each sequence to eliminate steps when infants were ramping up and slowing down, and eliminated segments that were less than 4 steps and were not forward, continuous, and straight. We used the fastest two sequences for further analyses.

We processed the 32 sessions with “natural gait” data as in Lee, et al. (2018). We used all bouts (or sections of bouts) that occurred on the instrumented floor in which infants took at least four continuous steps (to include a complete gait cycle on each leg), regardless of path shape or step direction; no steps were removed from these bouts during processing.

Protokinetics software calculated speed (distance from first to last step/time), step length (front to back distance between consecutive steps), and step width (side to side distance between steps); see Cole, et al., 2016 and Lee, et al., 2017. Because infants did not always take forward steps in straight lines during free play, values for step lengths and step widths were sometimes negative; thus, we calculated absolute values for each step as in previous work (D. K. Lee et al., 2018).

Results

Developmental predictors were infants’ age, walking experience, and three measures of gait proficiency in the straight-path test (speed, step length, and step width). The primary outcome measures were holding objects (calculated as a percent of walking or standing bouts in each of the 64 sessions) and exploring objects (calculated as a percent of holding bouts in each session). Of course, during all times when infants explored objects, they also necessarily held them. Given large individual differences in base rate of walking, we analyzed holding as a percent of walking bouts. To control for individual differences in rates of holding and because exploring necessarily required holding, we analyzed object exploration as a percent of holding bouts. Holding and exploring bouts while standing were analyzed in the same manner as while walking.

We also obtained "natural" gait measures (speed, step length, and step width) when infants walked on the instrumented floor during free play to assess the effects of manual actions on objects. For these analyses, we treated holding and exploring as predictors. Because the instrumented floor was only available for a subset of 32 sessions and because infants only walked on the floor during a subset of their walking bouts, the number of available sessions with natural gait measures was reduced. Of the 32 sessions, 28 sessions had bouts with no object in hand ($M = 8.07$ bouts), 28 had bouts while holding an object ($M = 6.54$ bouts), and 24 sessions had both types of bouts. Therefore, analyses of gait during exploration were reduced to 28 sessions, 27 sessions without exploration ($M = 4.33$ bouts), 21 with bouts of exploration ($M = 3.14$ bouts), and 20 with both types of bouts.

We used generalized estimating equations (GEEs) rather than ANOVAs for analyses to account for the subset of infants who had repeated sessions and/or sessions missing a condition (holding/not-holding, exploring/not-exploring); in addition, GEEs can model non-continuous outcome measures (Hardin & Hilbe, 2003). We tested effects of test age, walking experience, and three measures of walking proficiency (speed, step length, and step width) in separate models for each outcome measure. Results are reported in terms of Wald X^2. Preliminary analyses showed no effect of gender, so it was not included in further analyses.

Frequency of Object Interactions While Walking

During free play, infants spontaneously walked, stood in place, and engaged in activities that did not involve an upright posture such as sitting, crawling, and climbing on elevations. Across the dataset, infants generated 6189 walking bouts and 3926 standing bouts. The GEE showed that, on average, infants spent more time walking ($M = 28.27\%$ of the session) than standing ($M = 17.19\%$), $X^2 = 40.07$, $p < .001$. Infants produced 24 to 150 walking bouts in total ($M = 96.16$), and the number of steps per bout ranged from 1 to 127 ($M = 8.55$). Infants produced 21 to 115 standing bouts in total ($M = 60.53$). Walking and standing bouts were similar in duration ($M = 3.54$ seconds, $SD = 0.97$ and $M = 3.39$ seconds, $SD = 1.10$, respectively), $X^2 = 0.49$, $p > .10$.

Infants found the standard toys highly engaging. In most sessions (86%), infants interacted with at least 6 of the 7 toys at least once across upright, sitting, and prone postures. As illustrated in Figure 1B, infants showed a high level of interest in all of the available toys – the least popular object (the car roof) was played with in 84% of sessions while the most popular object (the xylophone) was played with in 98% of sessions. Moreover, infants interacted with the objects for varying proportions of the session across toys (Ms = 18–79% of the session across the 7 toys). Infants used the objects as designed (hugged dog and rolled car, shook/rolled ball and apple, pressed keys on xylophone and saxophone) and also discovered other affordances (stroked dog's ears, put car door and car roof on and off, poked fingers into openings on ball and into crocodile's mouth, fingered leaves on apple, etc.). Interacting with "found" objects was necessarily lower because each was available for only

1 or 2 sessions. Analyses for holding and exploring included all objects, both standard and found.

Given that infants walked frequently and enjoyed playing with the objects, did that lead them to frequently carry the objects? In a word, yes. The overall height of the bars in Figure 2A shows the percent of walking bouts where infants held objects. Each bar represents one session and sessions are ordered by infants' walking experience. Despite the potential cost of combining the old skill of holding with the new skill of walking, infants interacted with objects surprisingly often while walking—on average carrying objects in 33.28% of walking bouts. Every infant in every session carried objects while walking at least five times; and the proportion of walking bouts that including carrying ranged from 9.33% to a massive 95%. In fact, infants appeared to carry objects because carrying was intrinsically rewarding. Pooled across the dataset, most bouts of holding while walking ended with the object still in infants' hands (79% of bouts), rather than dropping, placing, or throwing objects, or giving objects to caregivers. Infants rarely dropped objects (3% of carrying bouts), suggesting that the new skill of walking did not substantially impair the older skill of object manipulation.

Infants also frequently explored held objects while on the move. The height of the colored bars in Figure 2A shows the percent of walking bouts during which infants explored a held object. Exploration occurred in 25.22% of carrying bouts (range 0% to 61.64%); in all but one session, infants explored a held object at least once. While walking, infants explored objects visually (M=14.15%, SD=9.26), manually (M=7.60%, SD=8.98), and with both visual and manual exploration (M=3.67%, SD=5.41). Note, in 1% of holding bouts, exploration data was not available for analysis.

Object Interactions in Walking versus Standing

Infants also held objects frequently while standing. Figure 2B illustrates the rates of holding objects and of various methods of exploring objects while standing for each session. On average, infants held objects while standing in 35.32% of walking bouts (see height of black bars in Figure 2B). Every infant in every session held objects while standing at least five times; and the proportion of standing bouts that including holding objects ranged from 10.39% to 97.44%. Exploration occurred in 41.48% of standing-holding bouts (range 3.92% to 76.00%); in every session, infants explored a held object at least once (see height of colored bars in Figure 2B). While standing, infants explored objects only visually in M = 21.02% of holding bouts (SD = 13.10), only manually in M = 10.67% of holding bouts (SD = 12.79), and both visually and manually in M = 9.66% of holding bouts (SD = 8.90); in M = 1% of holding bouts, exploration was off camera. However, neither rates of holding nor exploring while standing changed as a function of development.

Consistent with the idea that mastered and new skills are immediately integrated, we found that holding while standing was not more common than holding while walking, and there was no change over development (see constant height of bars in Figure 2). The left column of Figure 3 shows the percent of holding while walking and while standing for each session ordered by three measures of development: age, walking experience, and step length. If infants suppressed object skills to focus on walking, we would expect a clear preference to hold objects while standing, at least early in development when walking skill is poor. The intermix of symbols across sessions in the left column of Figure 3 shows clearly that this was not the case: Infants held objects both while standing and while walking, and did so throughout development.

Formal analyses confirmed that infants do not suppress object carrying while learning to walk. The percent of bouts that involved holding was not normally distributed, D_ns > 0.11, ps < 0.05, so we did a log transformation prior to running the GEE. The GEE confirmed that infants were equally likely to hold objects while walking (M = 33.28% of bouts, SD = 19.08) and standing (M = 35.32%, SD = 19.80), $X^2 = 2.83$, $p = 0.09$. And holding in both cases did not change with infants' age, walking experience, or walking proficiency (speed, step length, step width) in the standard straight-path test, all ps > .10. Likewise, the duration of walking bouts did not differ when infants held objects (M = 3.68 seconds, SD = 1.52) versus when they did not (M = 3.42 seconds, SD = 1.10), $X^2 = 2.23$, $p = 0.14$. Infants took more steps/bout while holding objects (M = 9.37, SD = 4.03) than while walking with hands free (M = 8.02, SD = 2.62), $X^2 = 10.22$, $p = .001$, with no change across development, all ps > .10—also consistent with the idea that new skills are immediately integrated into mastered ones without incurring a sharp cost.

Like holding, exploring objects did not change over development while walking and while standing (right column in Figure 3). However, in contrast to holding and consistent with the idea that already-mastered skills may be suppressed when new skills are being developed, infants were more likely to explore objects while standing than while walking (see prevalence of pink symbols above green in Figure 3 and inset bar graph). The GEEs confirmed more exploration while standing than walking, $X^2 > 65.07$, all ps < .001, but no change across development, all ps > .10.

Thus, infants do not completely suppress manual actions while walking, but do interact with objects selectively. Holding objects is equally common in walking and standing, but infants tended to use the more arduous skill of manual exploration more frequently while standing. Note, however, that all but one infant sometimes explored objects while walking; manual exploration was suppressed while walking, but not completely avoided. Finally, neither holding nor exploration changed over development; infants were highly motivated to carry and explore objects, regardless of their level of walking skill.

Selectivity of Manual Actions by Object Weight and Size

Do infants engage with objects selectively based on object properties? As shown in Figure 1C, infants did indeed hold objects differentially based on object weight. Of the 7 standard toys, infants held the light and medium weight toys (which were also smaller and more manageable) in more sessions than the heavy, oblong xylophone toy. With the "found" toys also included in analyses, infants held light or medium weight objects in 100% of sessions, but heavy objects in only 33% of sessions. Note, lower rates of carrying the heavy xylophone were not due to disinterest; indeed, the xylophone was one of the most popular toys. When we examined infants' interactions with objects regardless of whether they held objects aloft, they played with the lightweight toys (car roof or rattle ball) in 97% of sessions, the medium-weight toys (dog, car, apple, saxophone) in 100% of sessions, and the heavy crocodile xylophone in 98% of sessions.

To formally assess effects of object weight on holding, we compared the percent of walking and standing bouts in which infants held light, medium, and heavy objects (Figure 1D). Using an intercept-only model, the GEE confirmed that infants were less likely to hold heavy objects compared to both light and medium objects while standing and walking ($p < .001$), but held light and medium-weight objects the same amount ($p > .10$). The GEEs showed no change across development (*p*s > .10). To assess effects of object weight on exploration, we compared the percent of bouts in which infants held light, medium, and heavy objects and also explored them while walking and standing (Figure 1E). The GEE showed a main effect for object weight ($X^2 = 19.56$, $p < 0.001$), and more exploration while standing versus walking, $X^2 = 10.97$, $p = 0.001$. Follow-up tests revealed differences between light and medium objects (*p*s < .001), such that infants explored medium objects more than light objects, but no difference compared to heavy objects (*p*s > .10).

Unimanual holding also differed by object weight, but showed no difference between walking and standing (Figure 1F). We compared the percent of bouts in which infants held light, medium, and heavy objects unimanually while walking and standing. The GEE showed a main effect of object weight ($X^2 = 112.04$, $p < 0.001$), but no difference between walking and standing ($X^2 = 0.46$, $p > .10$). Follow-up tests revealed differences between light, medium, and heavy objects (all *p*s < .05), such that with increasing weight, infants were less likely to hold the object in one hand.

Cost of Object Interactions to Walking

Do infants actually incur a cost to walking proficiency when carrying or exploring objects, when they choose whether and how to engage with the objects? As expected (D. K. Lee et al., 2018), older, more experienced infants took faster, longer, narrower steps in both the standard, straight-path assessment and during spontaneous free play (Figure 4A-C). For statistical tests of correlations among developmental measures, we included only the first session in which infants contributed data to both variables for infants with multiple sessions. As shown in Table 1, measures of age, walking experience, and walking proficiency were intercorrelated, providing assurance that parents' reports of walking experience and lab-based measures of walking proficiency were valid, all *p*s < .05. Walking experience was a stronger predictor of proficiency than age: Partial correlations showed relations between walking experience and proficiency in the straight-path test when controlling for age, all *pr*s < .05, but not between age and proficiency when controlling for experience, all *pr*s > .10. Partial correlations also showed a relation between walking experience and speed during free play when controlling for age, $pr < .05$. As expected, speed, step length, and step width were also intercorrelated within tasks, all *p*s < .05. And measures of gait proficiency during the standard straight-path assessment were correlated with natural gait during free play, all *p*s < .05.

Presumably, falling would reflect the greatest cost of object interaction while walking. However, most walking bouts (98.2%) did not end in falls. Although infants incurred at least one fall in 70% of sessions, in 19 sessions, infants never fell while walking. With an overall fall rate of 1.8%, the conjunction of falling and object interaction was rare. Nonetheless, falling was equally rare while holding an object ($M = 2.08\%$ of walking bouts) and while walking with hands free ($M = 1.66\%$), $X^2 = 1.47$ $p > .10$. Figure 5A shows a “bow-tie” pattern: In approximately equal numbers of sessions, infants fell while holding an object, while not holding an object, or did not fall in either case; the GEEs showed no effects of holding versus not holding objects, all ps > .10. Exploring bouts ($M = 8.30$ per session) were necessarily rarer than holding bouts ($M = 33.11$ per session), so the conjunction of exploring and falling did not allow an accurate representation of the fall rate while exploring.

In contrast, more sensitive measures of cost—effects of object holding on natural gait measures—did suggest a cost in terms of the maturity of infants’ gait, consistent with the idea that integrating new and old skills comes with a cost (Figure 5B-D). Infants’ walking speed was slower while holding objects ($M = 38.50$ cm/s) than while walking with hands free ($M = 48.66$ cm/s), $X^2 = 10.95$, $p = 0.001$; their step length was shorter while holding objects ($M = 19.66$ cm) than not ($M = 22.95$ cm), $X^2 = 12.05$, $p = 0.001$; but their step width was not different while holding objects ($M = 12.30$ cm) than not ($M = 11.63$ cm), $X^2 = 3.63$ $p = 0.57$. The GEEs also revealed main effects of age, walking experience, and walking proficiency in the standard gait test, all ps < .05, but no interactions with holding versus hands free.

In contrast, exploring held objects did not appear to incur a cost to gait measures above and beyond the cost of holding itself. Although infants contributed sufficient natural gait data to analyze effects of exploration, the GEEs did not reveal reliable effects of exploring versus not exploring held objects while walking: Speed was similar while exploring held objects ($M = 38.70$ cm/s) compared to simply holding the objects aloft ($M = 38.83$ cm/s), as was step length while exploring ($M = 19.57$ cm) compared to simply holding ($M = 19.89$ cm), and step width while exploring ($M = 12.21$ cm) compared to simply holding ($M = 12.45$ cm), all ps > .10.

Discussion

Decades before formal reports of spontaneous object carrying were available, Gibson (1988) anecdotally observed that new walkers appear “astonishingly motivated” to carry objects; she marveled at “the joy of a novice walker in carrying small objects around” (p.33). Indeed, every infant in our study spontaneously carried objects. On average, they held objects on 33% of their walking bouts; one infant carried objects (a plastic cookie, the rattle ball, or the dog) in 95% of her 100 walking bouts. Moreover, we found that infants spontaneously explore objects by looking and/or manipulating while walking—the infant equivalent of texting while walking (Ms = 25% of holding bouts and 8% of all walking bouts). Although Gibson (1988) supposed that “the pure motive of carrying something somewhere…no doubt wears out fairly soon” (p. 33), we found that spontaneous carrying continues unabated across infant development. However, we also found that holding and exploring objects while walking incurs a reliable cost on gait patterns, and that infants selectively hold lighter objects more than heavier ones. How shall we interpret this set of findings?

Integration of Old and New Skills: Real Time and Development

Skills develop at different times in infancy, so infants possess well-established skills such as holding and exploring objects at the same time that they are acquiring new skills such as walking. How do infants juggle old and new skills in real time? One possibility is that they perform skills in sequence. For example, novice walkers could (and do!) walk to objects and then while in well-established standing and sitting postures interact with the objects. Alternatively, they could perform old and new skills concurrently—hold and explore objects while walking.

If infants suppress manual actions to focus all their attention on learning to walk, novice walkers should display less carrying than older, more experienced, more proficient walkers. This prediction was not borne out. Although previous work reported that the frequency of carrying increases with walking experience (Karasik et al., 2012), this developmental relation could have resulted from more frequent walking bouts in the more experienced walkers. Here, we normalized the rate of holding by the overall frequency of walking to take individual differences in spontaneous walking bouts into account, and we did not find increased carrying over development. Moreover, this study was the first to examine exploration while walking—a demonstration of multi-tasking that is especially impressive in infant walkers. Exploration, which necessarily involves carrying plus attention to object properties and fine motor actions, was present in new walkers and we found no evidence of increase over development.

Instead, manual actions on objects were immediately and spontaneously incorporated into the real-time activity of walking. Indeed, carrying objects and walking while exploring objects were prevalent at every point in infant development (Figure 2, Figure 3): Concurrent manual and locomotor actions were constant across infant age (12–19 months), walking experience (2 weeks to 10+ months), and three measures of walking proficiency (e.g., average step lengths of 13.79 to 50.10 cm in the standard straight-path test).

Selectivity of Manual Actions

Although infants incorporated manual actions into locomotion, they were sensitive to the demands of combining the old and new skills. Infants were highly motivated to play with objects while walking, but they did not do so indiscriminately. Although infants frequently held objects during both standing and walking, exploration was more frequent while standing. Visual and manual exploration of a held object are more sophisticated tasks than mere holding (Soska & Adolph, 2014; Soska et al., 2010); this kind of dual-tasking may have been too taxing for infants. Moreover, only a small percentage of walking bouts—including those containing exploration—ended with infants either dropping the object or falling. Thus, the lower rate of exploration while walking was not a result of infants attempting and failing to combine the two skills, either by losing the object or cutting a bout short. Rather, infants appear to suppress exploration while walking and selectively choose to explore objects from a stationary position—and they do so across development.

As in previous work with seated infants (Palmer, 1989; Ruff, 1984), we found similar evidence of selectivity in the way infants engaged with objects of different weights. Despite their interest in playing with heavy objects, infants relegated most interactions to times when the object rested on a surface, rather than holding it aloft. Given a choice of objects in free play, infants chose lighter, smaller objects for transport (Figure 1C-D). They also chose lighter, smaller objects to hold and explore while standing (Figure 1D-E). And given that most held objects were light, infants were more likely to hold them in one hand than two (Figure 1F). Selectivity of manual actions based on object weight was constant across development. Apparently, infants are sensitive to the properties of objects they encounter in naturalistic environments, and they spontaneously adjust their behavior accordingly. But adjustments are not related to walking experience: Whether new, unstable walkers or experienced, proficient walkers, infants spontaneously choose lighter, smaller objects to carry and explore.

Motivation and Cost

It is a central principle of motor control that changes in mass and in the location of the center of mass alter the biomechanical constraints on balance (Shumway-Cook & Woollacott, 2017). Carrying objects does both. The object’s weight functionally increases body mass, making balance more precarious. Top-heavy loads, asymmetrical loads, and loads on an appendage exacerbate the problem by changing the location of the center of mass. Holding even a light object in hand can alter arm position and thereby change the location of the center of mass. Balance in novice walkers is already at risk, so carrying objects should increase the risk. Previous work confirmed that load carriage impairs gait patterns and increases the likelihood of falling (Garciaguirre et al., 2007; Hsu et al., 2016; Mangalindan et al., 2014; Vereijken et al., 2009). The current study also showed negative effects on walking while holding objects compared with walking hands-free (Figure 5B-C). In contrast to earlier work that failed to normalize frequency of falling by the frequency of walking (Karasik et al., 2012), we found no evidence that holding objects caused infants to fall more frequently (Figure 5A). But we did find a significant impact on walking gait: When carrying objects, infants walk slower and take shorter steps.

Why then does holding and exploring objects or even visually exploring a scene reduce postural sway while standing (Claxton et al., 2013; Claxton et al., 2012)? Posture normally functions to provide a stable base for other actions (Reed, 1982). When those other actions require visual fixation on a target, infants allocate resources to stabilize posture so as to stabilize gaze. Similarly, infants in the current study were more likely to explore objects while standing than while walking (Figure 3D-F), perhaps because the stationary posture allowed them to better fixate the object. Yet curiously, we found that when infants *did* explore objects while walking, they incurred no additional cost beyond that of holding (Figure 5B-D). Perhaps exploration on the move had no additional cost because infants were already walking more slowly and taking shorter steps due to holding the object; additional adjustments to gait may not have been necessary.

Regardless, interacting with objects while walking—either holding or holding and exploring—has a cost relative to walking hands-free. But it was a cost that infants appeared happy to incur. At every point in development, decisions to produce actions are a product of motivation and the *perceived, not the actual, cost* (Trommershäuser, Maloney, & Landy, 2008). Perceived cost is determined by the individual, and may differ from researchers’ assessment of actual cost. Adults may decide to run a marathon—and even to race while wearing crazy costumes and carrying props—because their level of motivation outweighs the very real costs. Similarly, infants’ motivation to transport objects appears considerably higher than the perceived cost. They occasionally carry objects to interact with caregivers and to interact with other objects (Karasik et al., 2011, 2014). But most frequently, infants carry objects for no apparent reason other than their enjoyment in carrying (Gibson, 1988; Karasik et al., 2012). Most bouts conclude with the object still in infants' hand. Like NYC marathoners whose motivation to run is simply to run, even with crazy props in hand, infants' motivation to transport objects is simply to walk, often with odd "found" objects in hand (Cole et al., 2016). The actual cost of modifying gait may constitute only a negligible perceived cost to the infant in the face of infants' zeal for carrying objects.

Conclusions

Some skills such as emotion, language, and constructive object play compete for infants' attention. As a new skill appears, the more and less established skills must be sequenced in real time. Other skills develop more cooperatively. The earlier developing skills of holding and exploring objects are immediately incorporated into the later developing skill of walking. Despite a reliable cost to locomotion, at every point in the development of walking infants are highly motivated to carry something somewhere.

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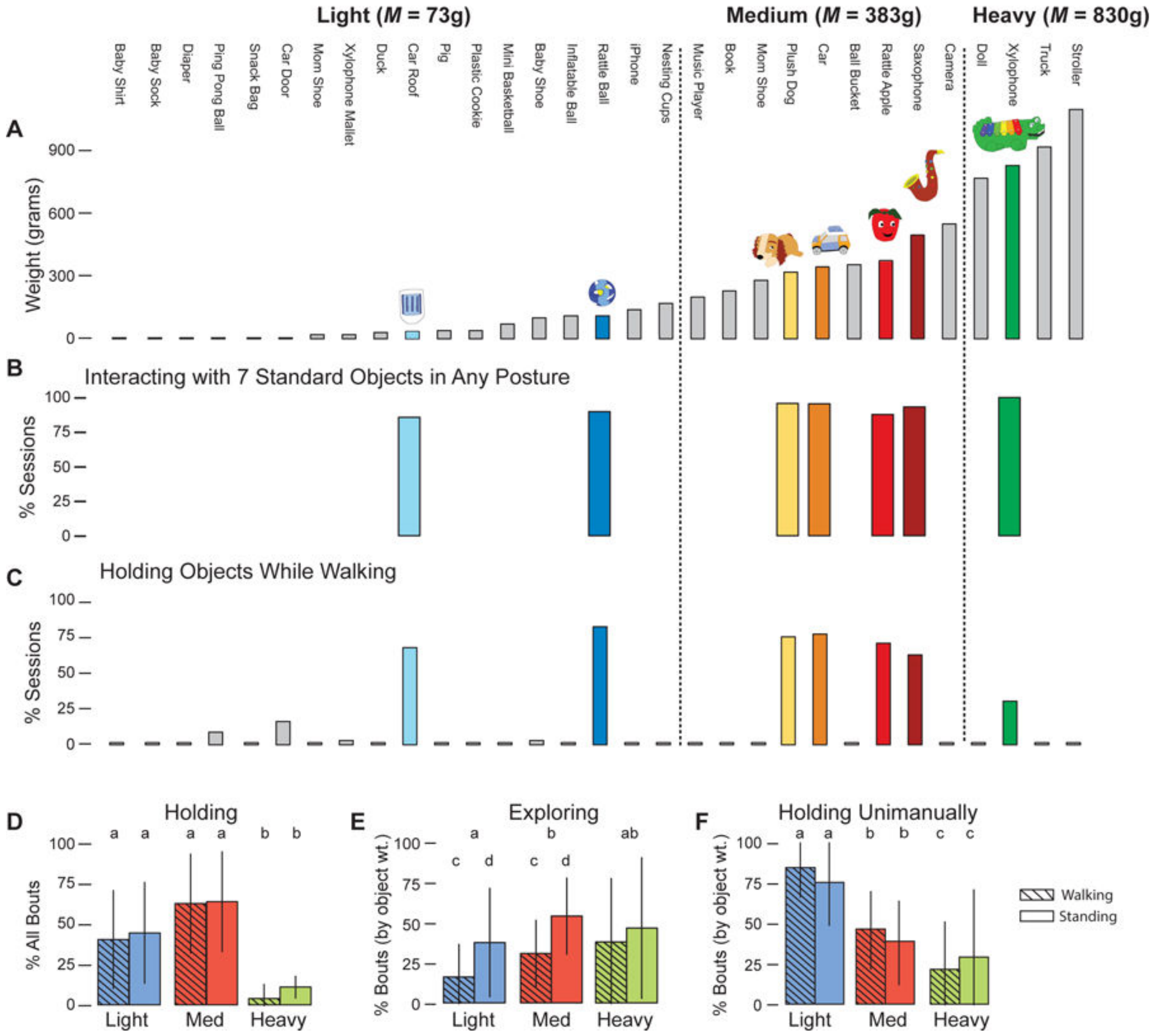

Figure 1.

Infants' manual actions on objects by object weight. (A) Objects available for free play, ordered by object weight. Colored bars denote the 7 toys available in all 64 sessions; gray bars denote "found" objects available in only 1 to 12 sessions. Analyses included both standard and found objects. (B) Percent of sessions in which infants interacted with each of the 7 standard objects available in every session. (C) Percent of sessions in which infants held light, medium, and heavy objects while walking. Gray bars are necessarily low because found objects were unavailable in most sessions. (D) Percent of walking bouts (striped bars) and standing bouts (solid bars) in which infants held light, medium, and heavy objects. (E) Percent of light, medium, and heavy object holding bouts in which infants both held the object and explored it while walking (striped bars) and standing (solid bars). (F) Percent of light, medium, and heavy holding bouts in which infants held the object unimanually while walking (striped bars) and standing (solid bars). Superscripts in D-F denote differences between conditions.

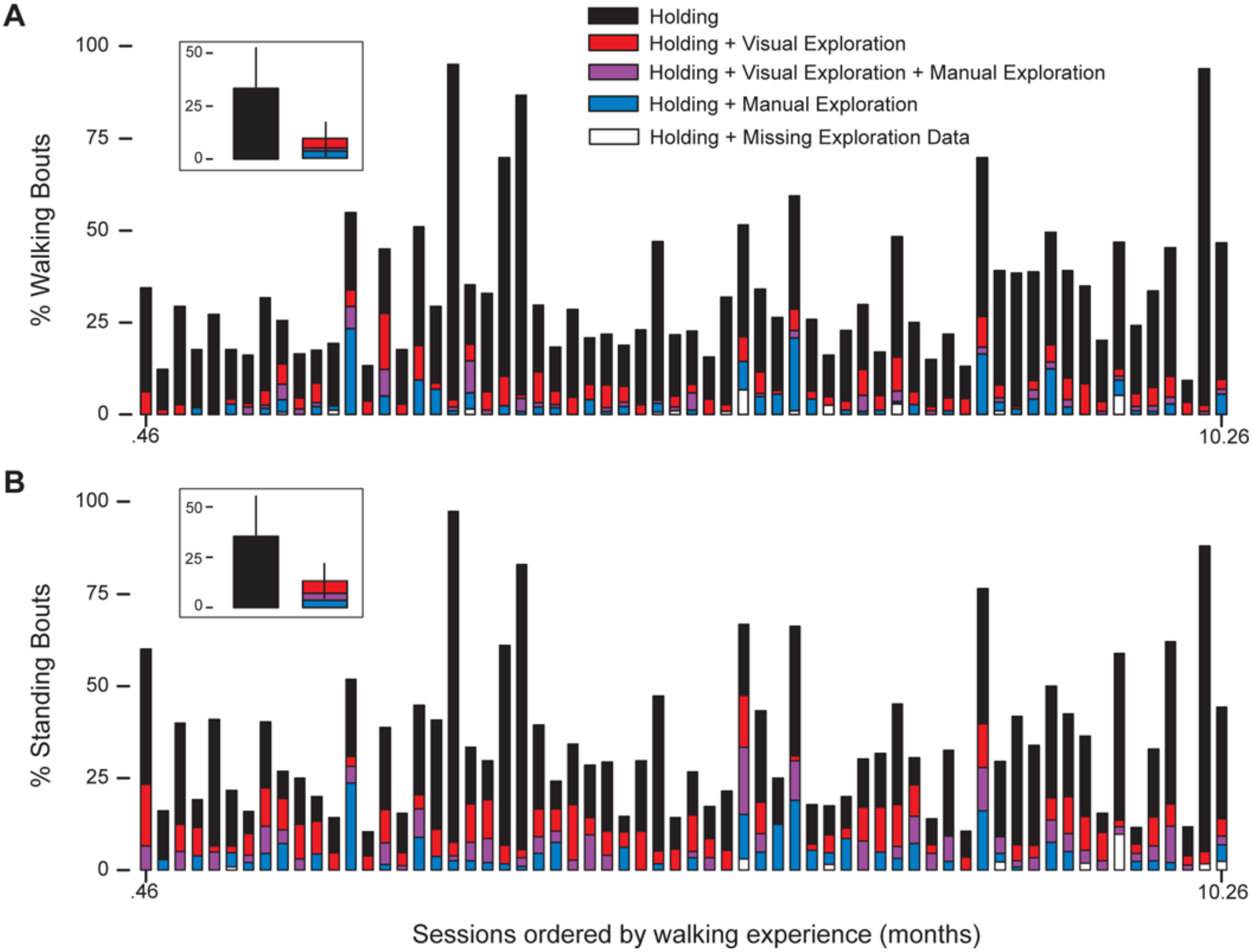

Figure 2.

Frequency of holding and exploring objects while (A) walking and (B) standing across walking experience. Bars represent the percent of bouts in each session where the infant held (black bars), visually explored (red bars), manually explored (blue bars), or both visually and manually explored (purple bars) objects in hand while walking and standing. White bars denote bouts in which the infant's hands or face were not available for coding exploration, but coders were still able to infer object carriage. Red, blue, purple, and white bars denote bouts when infants had objects in hand, so the total height of the bars show each infant's overall rate of holding objects while walking or standing. Sessions are ordered by infant's walking experience. Insets above each panel show the average percent of bouts in which infants held (black bars) and additionally explored (colored bars) objects.

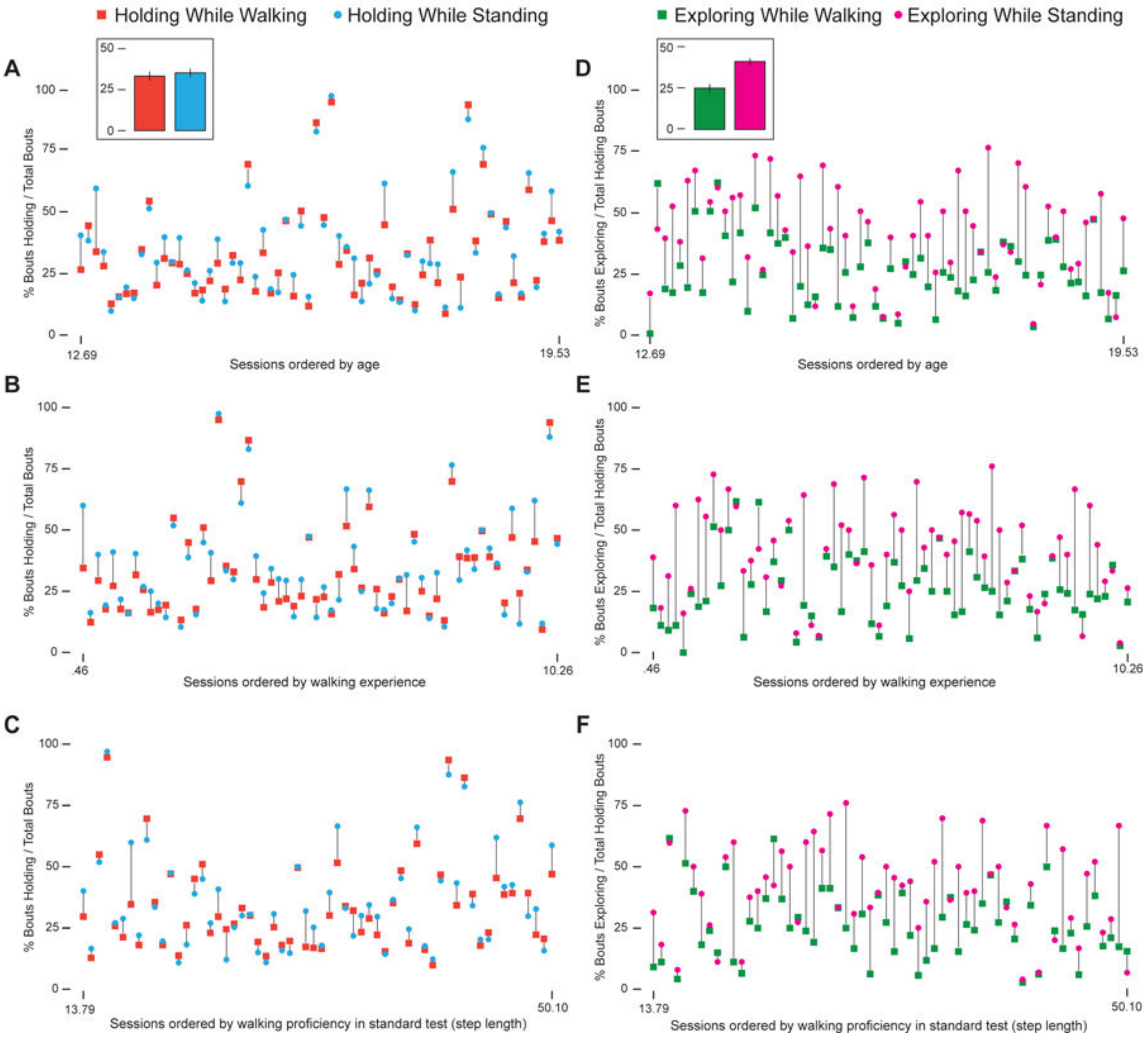

Figure 3.

Manual actions on objects while walking and standing across development. Left column shows holding as a percent of walking or standing bouts. Right column shows exploring as a percent of holding bouts while walking or standing. Each pair of symbols represents one session while walking (squares) and standing (circles). To view effects of holding and exploring across development, sessions are ordered in each graph by (A and D) age at test, (B and E) walking experience, and (C and F) walking proficiency based on step length in a standard straight-path assessment. Comparisons between the pattern of squares relative to circles show that holding did not differ between walking and standing, but exploration was more prevalent while standing than while walking. Insets at the top of each column show the overall effects of walking versus standing for holding (left column) and exploring (right column).

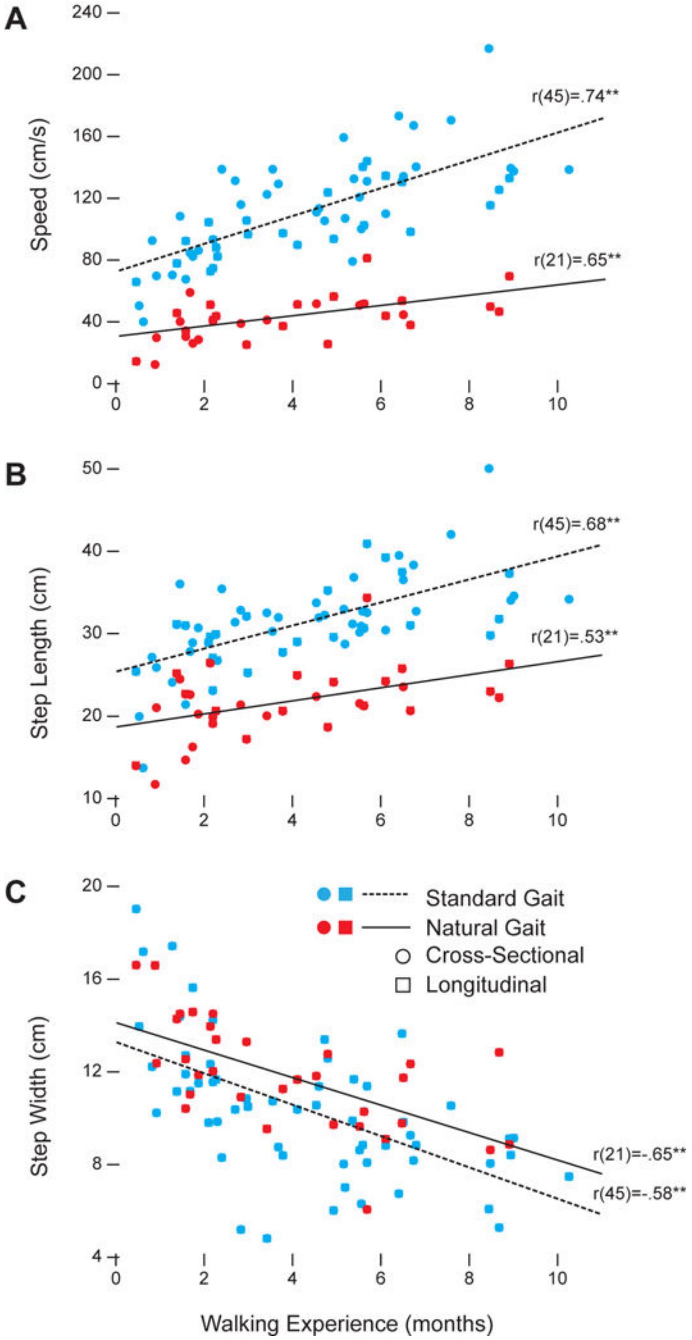

Figure 4.

Walking proficiency across months of walking experience in the standard straight-path test and during free play. (A) Speed. (B) Step length. (C) Step width. Blue symbols and dashed best-fit lines denote standard gait. Red symbols and solid best-fit lines denote gait in free play. Circles denote infants tested only one time and squares denote infants tested at 2–3 sessions.

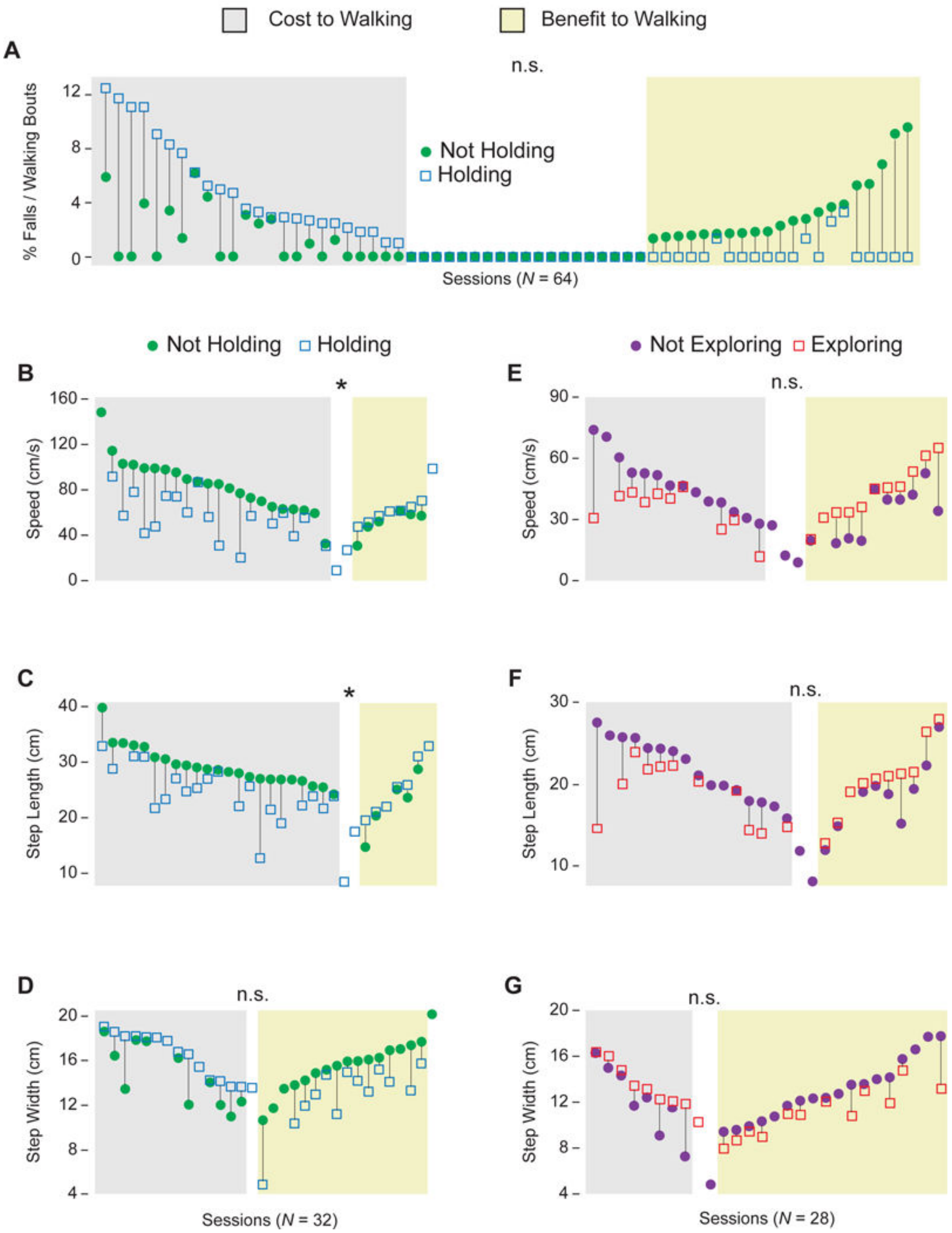

Figure 5.

Costs and benefits of performing manual actions on objects while walking in terms of (A) falls, (B, E) speed, (C, F) step length, and (D, G) step width. Gait measures reflect “natural” gait during free play. Each pair of symbols represents one infant at one session. Green circles denote walking without holding an object and blue squares denote walking while holding an object. Purple circles denote walking while merely holding an object and red squares denote walking while exploring holding an object. Gray regions show evidence of cost in the majority of sessions for speed and step length (i.e., slower, shorter steps) while holding an object compared to not holding an object, but not for step width (larger step widths in approximately half of the sessions) or falls (sessions split about evenly among more falls while holding, more falls while not holding, and no falls in either condition). In contrast, the gray regions show no evidence of cost on gait measures while exploring an object compared to merely holding the object. Yellow regions reflect the small number of sessions that show benefits: That is, (A) fewer falls while holding objects, (B, E) faster speeds, (C, F) longer steps, and (D, G) narrow step widths while holding or exploring objects.

Table 1.

Correlations (first value) among test age, walking experience, and walking proficiency in the straight-path assessment and during free play and partial correlations (second value, controlling for age).

	Walking Experience	Speed (straight-path task)	Step Length (straight-path task)	Step Width (straight-path task)	Speed (freeplay)	Step Length (freeplay)	Step Width (freeplay)
Age	$r(49)=.82^{**}$	$r(45)=.62^{**}$	$r(45)=.60^{**}$	$r(45)=-.50^{**}$	$r(21)=.52^{*}$	$r(21)=.50^{*}$	$r(21)=-.55^{**}$
Walking Experience		$r(45)=.74^{**}$	$r(45)=.68^{**}$	$r(45)=-.58^{**}$	$r(21)=.65^{**}$	$r(21)=.53^{**}$	$r(21)=-.65^{**}$
		$pr(44)=.52^{**}$	$pr(44)=.40^{**}$	$pr(44)=-.34^{*}$	$pr(20)=.46^{*}$	$pr(20)=.25$	$pr(20)=-.41$
Speed (straight-path task)			$r(45)=.88^{**}$	$r(45)=-.63^{**}$	$r(20)=.54^{**}$		
Step Length (straight-path task)				$r(45)=-.54^{**}$		$r(20)=.60^{**}$	
Step Width (straight-path task)							$r(20)=.76^{**}$
Speed (freeplay)						$r(21)=.90^{**}$	$r(21)=-.71^{**}$
Step Length (freeplay)							$r(21)=-.63^{**}$

For infants with repeated sessions, we included only the first session in which they contributed data to both variables in the correlations.

*r*s = Pearson correlation coefficients

*pr*s = partial correlations, controlling for age

[*] p < .05

[**] p < .01

Walking experience = number of days between walk onset and test

Speed = (absolute value of the distance between first and last step)/time

Step length = absolute value of the front-to-back distance between consecutive steps

Step width = absolute value of the side-to-side distance between consecutive steps