STRATEGIC LOCOMOTION IN YOUNG WALKERS

by

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Certificate of Approval

This is to certify that the accompanying thesis by Aislyn Booth & Serena Sanders has been accepted in partial fulfillment of the requirements for graduation with Honors in Psychology.

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Dr. Emily Bushnell

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Abstract

One reason that young children make the switch from crawling to walking is so that they can move around with their hands free to carry interesting things, like toys. As young walkers gain experience and skill, they are likely to want to carry more (and bigger) items− sometimes through doorways or into tight spaces. This often demands planning a locomotion strategy involving an item that extends past the child's body height or width. In the current study, young children were asked to carry extended objects through small apertures, either tall objects through short doorways, or wide objects through skinny doorways. Their successes in completing the task, their adjustment strategies, and improvement over trials were evaluated. All children, even if they collided the object into the doorway, made appropriate adjustments that allowed them to cross through the apertures. Older children (24-37 months) made fewer errors (collisions) than younger children (15-23 months) for both apertures, and older children also exhibited more mature adjustment strategies. Both age groups made more errors on the tall, skinny doorway, but showed improvement over trials in this case. The age differences indicate an important role of long-term experience, while the improvement over trials indicates an effect of short-term experience. Our results contribute to growing literature exploring "embodied cognition"- the ways that planning and problem solving are involved in seemingly simple motor activities.

Strategic Locomotion in Young Walkers

It is a momentous occasion when a baby takes its first steps. However, after these first steps, the challenge is not over. Throughout life, people have to meet locomoting challenges posed by the environment, for example, hills, stairs or uneven ground. Changes to one's body can also present locomoting challenges, for example losing weight, gaining weight, being pregnant, or growing can also influence balance, stride and gait. The work to meet these locomoting challenges is especially difficult in infancy, when children grow remarkably fast, and new facets of the environment are introduced to them every day. There is always planning, choice, decision-making and strategizing involved in the process of successfully managing locomoting challenges. This can be examined in what is often referred to as embodied cognition. Embodied cognition implies that significant aspects of cognition are involved in actions of the physical body (Wilson, 2002). Even though crawling, walking and other aspects of being independently mobile seem like simple actions, they involve complex dynamic interactions between various motor abilities and mental processes like deciding, predicting and planning.

Developing the ability to walk

The skill of walking engenders advanced spatial understanding and cognitive development in infancy, and demands planning and problem solving to confront the complex environment that infants are motivated to explore (Biringen et. al., 2008; Witherington et. al., 2005). Most babies take their first steps between 9 and 12 months, and are walking well by 15 to 17 months. Walking requires leg and trunk strength to support an upright posture, as well as the ability to balance on one and two feet while moving (Thelen & Ulrich, 1991). There is also an element of coordination that is necessary for walking babies. In the early stages of walking, young toddlers learn through experience, in a trial-and-error dominated progression. During the crucial learning period of twelve- to 19-months, toddlers average 2,368 steps and 17 falls per hour (Adolph et. al., 2012). This immense locomotor experience is what constitutes the natural progression of practice necessary to become a better walker. Competence in walking ability is specifically shown in stepping patterns that show increasingly mature gait (longer, narrower and straighter strides as opposed to shorter strides with wide foot placement), increased amounts of spontaneous walking, as well as markedly fewer missteps and falls (Cole, Lingeman, & Adolph, 2012).

Environmental challenges

Infants must learn to alter their walking to climb stairs, to traverse sloping surfaces such as hills and ramps, and to traverse unstable surfaces like mud, gravel and sand, as well as to step over or around gaps or barriers in the pathway. Infants' emergent ability to cope with such variations in the ground surface has been elegantly documented by various researchers with slightly whimsical studies utilizing circumstances unfamiliar to infants, such as ball pits, sticky shoes, waterbeds, and unevenly weighted backpacks (e.g., Adolph & Avolio, 2000; Adolph, Karasik, & Tamis-LeMonda, 2010). Research done with a series of steep slopes (10°, 20°, 30° and 40°) showed that while both crawling infants and walking toddlers overestimated their ability to ascend these slopes, walkers showed improved perception of risk and consequence in descent by altering their position by sitting or backing down the slope to ensure a safe and successful slide (Adolph, Eppler, & Gibson, 1993). In this study, crawlers, who have less experience altering their technique for various types of surfaces, went down even the steepest slopes head first, which consistently resulted in falling. This demonstrates their lack of accurate perception, due in part to the fact that crawling on all fours is a more stable mode of transportation (with less severe consequences if one does fall) than the balancing act of upright locomotion. The walkers' demonstrated ability to feel out situations and modify their plan of action shows how decision-making cognition can be tied to physical locomotor experience and ability. A similar pattern was shown when walkers and crawlers were faced with crossing a waterbed. Walking toddlers explored with their hands to get a feel for the physical qualities of the surface they encountered, then demonstrated plan formation in choosing to crawl (traveling on four limbs is a more stable form of locomotion than on two) across the wavering ground (Gibson et. al., 1987).

As toddlers are developing strength and competence in walking on varied surfaces, they are also encountering barriers in their pathway. Common barriers such as toys, pets, stairs, or large sticks or logs that are at floor level pose challenges to young walkers as toddlers must adjust their step height, their gait length, or even change their locomotion from walking to crawling or climbing over the barriers. The child's modifications in their locomotion are visually guided and specialized to the particular challenges that the barrier creates. Successfully crossing barriers is a skill that children eventually master. A study done with 18 and 24 month old children showed that walking experience predicted toddler's ability to cross barriers better than walking skill (Kingsnorth & Schmuckler, 2000). In this study, walking skill was assessed using a footprint analysis of gait (step width, step length, stride length, etc.) and walking experience was assessed through parent's self report of when their child started to crawl, stand upright independently, and locomote upright. As shown, experience with varied obstacles makes one better prepared to confront new ones.

Apertures and perception

In addition to barriers, most children are bound to encounter various apertures in their daily lives, including doorways and tunnels at home and in places like playgrounds and museums. Some of these apertures are meant to be used as a passageway, and some of them will be tempting to cross through, even though they were not. If a toddler walks under a desk or table while playing, they will need to adjust their height by crouching while walking, which presents challenges in balance and leg strength. Sometimes two pieces of furniture or two trees create a tight space that a toddler will want to squeeze through. This action requires the toddler to change their body orientation and perhaps walk sideways through the space. In order to complete this maneuver successfully, children need to reasonably estimate their size in comparison to the size of the aperture. Even at the early stages of walking ability, children are sensitive to perceiving possibility and impossibility in terms of openings that they can fit their body through (Franchak & Adolph, 2012). In this study, toddlers stood on a table that was partially divided by a wall. On one side of the table, the wall did not quite reach the edge of the table and this left a small passageway that the infant would attempt to walk through to reach the other side of the table. The size of the passageway was specialized for children so that sometimes it was too small for them to successfully pass through. Additionally, another wall could be placed along the edge of the table with the passageway, perpendicular to the wall dividing the table. This wall made falling off the edge of the table impossible. When urged to pass through the opening, 17-month-old toddlers were less likely to attempt walking through the opening when the penalty of falling was present (ie. when the wall on the edge of the table was not there), than when the penalty of "merely" getting stuck between the two walls was present. This indicates that children at this age are able to successfully judge impossibility when the risk involves a more dangerous consequence. This indicates that infants as young as 17 months have an awareness of the extension of their bodies (Franchak and Adolph, 2012).

Common across all these various ways that locomotor challenges present themselves, is the way in which one has to adjust how to maneuver the body. Infants are required to actively, and strategically, test the limits of their bodies and surroundings to ascertain the best way to achieve their goal; whether that is crossing a water bed, climbing over something in the way, or squeezing through a tight space. These potential adjustments include, but are not limited to, crouching, shifting to a sit and scoot position, traveling on all fours, or turning the body for a more advantageous angle for movement.

Complexity of carrying

One reason that influences young children to make the switch from crawling to walking is so that they can move around while having their hands free to grab, feel, or carry interesting things, like toys. Karasik et. al. (2012) studied the role of spontaneous carrying in crawling and walking infants of 13 months and found that carrying occurred more often in walkers than in crawlers. Some anthropologists posit that carrying was probably central to the natural selection process promoting evolution from quadrupedal to bipedal locomotion in humans, and carrying has since been an important feature in all-human cultures. This ability to carry objects becomes possible as locomotion increases and matures. Interestingly, it was also found that both crawlers and walkers were less likely to fall when carrying, suggesting that carrying forces more attention and careful walking (Karasik et. al., 2012). Additionally, carrying can require adjustments in posture, stride, and balance in response to the nature of objects a person is holding while they walk.

As young walkers gain walking experience and skill, they are likely to want to carry more (and bigger) things to more places− sometimes even through doorways or into tight spaces. This often demands planning a locomotion strategy that involves an item that extends past the child's body height or width. Even in adults, this is a task that is sometimes failed. For example, truck drivers often drive their tall vehicles under overpasses with low height limits, causing wreckage. Valet drivers have also been known to collide roof racks of their client's cars into low-clearance parking garages.

Carrying ability

When carrying an item, it becomes necessary to be aware of how one manages their steps and rebalances their body to accommodate appropriately for whatever it is that one may be transporting. The properties of an object affect how, and how successfully, one walks with it. Children are sensitive to specific object properties due to exploratory experience that occurs earlier in development (Rochat, 1989; Ruff, 1984). Once children begin to walk, they must learn that carrying an object often requires postural compensation that directly corresponds to the weight of the item in order to balance one's center of mass (Bushnell & Clearfield, 2009). Carrying also occupies one or both hands, and can interfere with the alternating arm swing and stride that are seen in maximally efficient walking patterns. A large object that requires both hands to hold would even preclude using the arms to maintain or "catch" one's balance. Walkers with more experience tend to demonstrate a greater ability to manage heavy or large objects (Bushnell & Clearfield, 2009).

Even without the use of one's hands, carrying while walking can add difficulty. At 14 months, infants walking with weighted backpacks showed signs of disrupted gait patterns and less mature footfall patterns (Garciaguirre, Adolph, & Shrout, 2007). Additionally, infants with less walking experience were more adversely affected by the weighted backpacks showing that ability to carry extra weight while walking increases with increased walking experience.

Cumulative complexity

As children develop, they manage to build action plans that they can consistently rely on when walking and maneuvering through the wide variety of environmental hurdles that they might encounter in their daily lives. How are these challenges managed when the additional complexity of carrying items is added to the equation? While the ability to confront environmental obstacles, and the ability to carry diverse objects each come with a certain degree of difficulty, the difficulty of combining these two challenges is potentially more complex than the sum of the original challenges, separately. This comprises what is known as "cumulative complexity", a term originally coined to describe children's sequence of language acquisition (Brown, 1973). Encountering environmental obstacles *while* carrying a large, heavy, or unequally weighted item leads to a whole new level of complexity for infants, and can also pose a difficulty for adults. Imagine how hard it can be to shift multiple bags of groceries in a way that will successfully allow one to open the car door without dropping the food or getting tangled up in the maneuver. To translate this onto another example of cumulative complexity that adults face in locomotion, imagine combining the difficulty of walking while pregnant, and the difficulty of walking on an icy or slick surface. The cumulative complexity of walking on ice, while pregnant, would require a new set of adjustments to compensate for both difficulties simultaneously. The way that infants deal with this type of heightened complexity is a relatively understudied area of child development.

Goal-directed problem solving

Prior to becoming independently mobile, infants develop strategic plans for fine motor movements, such as reaching and grasping (McCarty et al., 1999). Goal-directed problem solving tasks have been observed in infants aged 9, 14, and 19 months old (McCarty et al., 1999). In the study, participants were presented with a spoon in various orientations and their initial grasping of the spoon and corrections of grasp were coded to examine strategies used by infants to accomplish the goal (eating food loaded onto the spoon). The researchers observed that nine month olds more frequently made initial grasp errors and attempted fewer corrections of grasp, resulting in a failure of goal attainment (sticking the handle side of the spoon in their mouths). Fourteen month olds still made grasp errors, but were more likely to make corrections of grasp to attain the goal (getting the food into their mouths). The 19-month-old participants were more likely to adjust their initial grasp in order to efficiently attain the goal without making any errors. The researchers concluded that by 19 months, most infants are able to anticipate future outcomes and devise appropriate behavior solutions before grasping and maneuvering objects, thus demonstrating plan formation and accurate spatial perception of objects. Specifically, the timing of the change in hand orientation in the process of grabbing the spoon came earlier, or further "ahead" of the goal, therefore was more mature, in 19-month-old toddlers than in the nine or 14 month olds.

McCarty's Four-Stage Model

McCarty et al. (1999) formulated a four-stage model that represents the development of an action plan, specifically modeled in their study of infants maneuvering a spoon with food on it. This model assumes that there is implicit motivation for the child to predict the consequences of his or her actions on the environment, that finding an efficient solution is a reasonably motivating goal for the child (Rosenbaum & Jorgensen, 1992), and that the standard of efficient action increases with age. The model outlines four strategies with incrementally increasing degrees of planning involved in each. The first involves feedback control, meaning the child perceives the situation and acts using an automatic plan of action, not taking into account the potential problems they will confront in doing so. For example, the child will use their dominant hand to directly grasp the closest end of the spoon with the food on it, failing to realize that this will not always be an effective eating strategy. The second represents a partially planned model, in that some but not all of the actions are planned before action takes place. This means that the child will have to make an adjustment to their plan mid-action (for example, rotation or grip change mid-transport of spoon to mouth), making this an ultimately successful, but inefficient strategy. The third strategy shows that the sequence of actions is fully planned. In this case, the child will have evaluated the situation mentally based on visual information, and has planned a course of action before beginning. This is a more mature strategy, but involves means-ends problem solving, meaning that the problem solver (the child) will get an idea of the ideal end result, and work backwards to determine the best strategy to arrive at that point. For example, they will understand that a radial grip will be the easiest way to get the food on the far end of the spoon into their mouths, then orient the same hand, or use the other hand to achieve this grip. While this will result in success, it requires thought on every trial. The last strategy is evident when the solution has been discovered confidently enough that the action plan has developed into a heuristic in the child's mind. This heuristic enables the child to reach their goal repeatedly without careful thinking and planning on each trial, and in this sense, the 4th stage of the model is much simpler, because it is no longer dependent on carefully connecting perception and action. With experience and age, this model shows how post-hoc realization evolves into pre-hoc decision-making.

We believe this model serves as a potential transferable framework for the planning and problem solving that occurs alongside motor behaviors *other* than grasping spoons, specifically, when infants become independently mobile, and are carrying items while walking. In terms of locomotion while carrying objects, it is reasonable to expect that a child's method of dealing with this type of cumulative challenge matures with age, which generally brings increased exposure and experience in a varied range of settings. Thus infants carrying objects down slopes or through apertures may progress through a sequence similar to the McCarty model outlined for reaching. For example, young walking infants might confront perceived risk by refusing to move, slightly older infants might make "on-line" adjustments in the middle of the task, or as a response to failure, and those with even more experience will creatively problem solve and form a strategic plan ahead of time without having to experience failure.

Current study & Hypotheses

The current study is to investigate young walkers' strategic adjustments to combat the cumulative complexity that comes with carrying extended objects through tight spaces. The challenge of maneuvering items that are too tall to fit through a low opening, or too wide to fit through a narrow aperture requires adjustment of either the body or the item to succeed. This scenario combines the planning and strategy to confront the challenges posed by apertures while simultaneously necessitating embodied cognition seen in the adjustments of the inconveniently shaped objects being carried. A poster tube fitted with rigid handles, priming a horizontal carrying position, and a Styrofoam frame with rigid handles, priming a vertical carrying position, were presented to children (15-37 months). Toddlers carrying the tube oriented horizontally were asked to walk through a tall, skinny doorway, while those carrying the frame vertically were asked to walk through a short, wide doorway. The dimensions of the objects and doorways were designed so that any toddler could fit through each doorway on his or her own, but so that the tube and frame would not allow the child to cross the opening without deliberate adjustment of his or her body, and/or the object. The mismatch of doorway and object size forced the children to implement a strategic locomotion plan to successfully walk through the apertures; otherwise they would collide the object into the doorway. A series of trials explored whether adjustments become more effective and efficient with short-term experience.

Following McCarty's model, we expect younger children (15-24 months) to initially fail this task before implementing a successful plan to cross the doorway, colliding the tube into the doorway before re-gripping or reorienting to pass through.

Older children (28-37 months) may anticipate the orientation problem, alter their grasp or body orientation, and successfully cross through without collision. The latter represents a planned strategy to confront the challenge, and signifies greater spatial understanding of both one's body and the carried objects. We hypothesize that due to the opportunities for experience that exist within the long term development between our two age groups (one year, on average), older children will be better at confronting this challenge than younger children, both in terms of success crossing through and adjusting earlier in the approach to the doorway. Due to a lack of relevant research on the topic of toddler's perceptual sensitivity to short openings versus narrow vertical openings, we were not able to form hypotheses about possible differences between confronting the separate challenges of doorways that are short and wide, compared to doorways that are tall and skinny.

Younger children who initially fail may show signs of earlier plan formation with successive trials. We hypothesize that with increased experience carrying objects through apertures, children will develop greater sensitivity to spatial extensions of their bodies and will show signs of plan formation when carrying objects through openings. This will suggest that spatial understanding of the relation between size of objects and apertures can, in fact, be learned with experience.

The purpose of this study is to explore the age differences in decisions, strategies and planning skills exhibited by toddlers to confront the challenge of carrying items that are either too tall or too wide to fit through a given aperture. Our results will contribute to a growing body of literature exploring embodied cognition and the ways that strategic planning and problem solving are involved in seemingly simple motor activities.

Method

Participants

Eighteen infants were included in the final sample (7 males, 11 females), divided into two age groups, under-two years old (8 infants) and over-two years old (10 infants). The under-two year old infants ranged from 15 to 23 months of age (M = 19.0 months, SD = 3.1 months; two boys and six girls; three biracial and five Caucasian). The over-two year old group infants ranged from 28 to 37 months of age (M = 33.4 months, SD = 3.1 months; five boys and five girls; three biracial (not otherwise specified) and seven Caucasian). Eight additional infants were also tested but not included in the final sample, because they were shy, fussy, uncooperative or otherwise uninterested in doing the task. Participants were solicited through email listservs, town community websites, and informational flyers posted at local day care centers, the public library, and community centers. Most participants were middle class and presumed to be healthy and developing normally.

Materials

A freestanding wooden room divider was built to split the Infant Development Lab (Figure 1). The divider was 8 feet wide and 5 feet tall and stretched almost completely across the width of the room. The remaining foot of space between the divider and the wall was blocked off with pieces of plywood. The divider had two doorways cut out of it: one 1.5 feet wide and 4.5 feet tall, designated to be the tall/narrow door condition, and the other 4 feet wide and 3.5 feet tall, designated to be the short/wide door condition. The doorframes were lined with black tape to highlight their boundaries and reduce potential for splintering edges. Each doorway could be covered by a sheet of opaque fabric (cut to appropriate size for each door) attached to the divider with Velcro, leaving only one door open at a time.

Children were asked to carry two cylindrical cardboard poster tubes (three feet long, four inch diameter) and one Styrofoam rectangular frame covered in tape (three feet long, one foot wide) (Figure 2). The tubes were fitted with two handles each, attached 6 inches apart in a straight line centered along the length of the tube. This placement primed a horizontal carrying of the tubes. The rectangular frame was also fitted with two handles, attached on the outside of each vertical edge, 4 inches from the bottom of the frame. These handles primed a vertical carrying position. The handles are black, lightweight, metal, drawer handles screwed into the tubes and the frame. Two lightweight plastic jars filled with colorful blocks were used as control stimuli (they could easily be carried through both doorways without an adjustment).

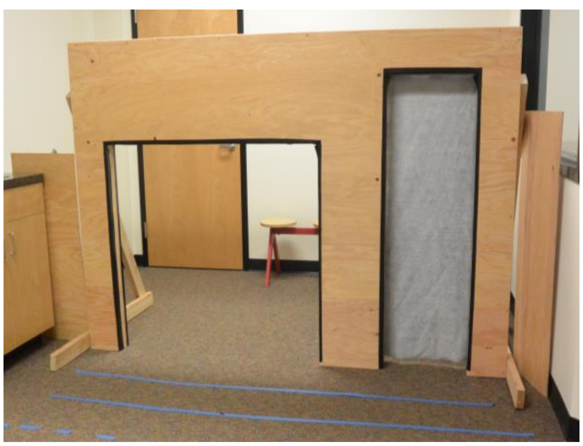


Figure 1. Room divider with two doorways, one short and wide, one tall and skinny. Pictured here with the tall/skinny doorway closed.

Figure 2. Items that children were asked to carry: Two poster tubes, the tall frame, and two lightweight plastic jars.

A goal bucket on the other side of the wooden divider was a tall plastic recycling bin with jingle bells on the bottom and stands behind the closed doorway. The role of this goal bucket was to provide motivation for continuation of the task; when items are placed into it, the bells in the bottom jingle. This position switches when one doorway is closed and the second is opened. Two digital cameras were used to record the children's behavior during their time in the lab. One video camera positioned to the right about six feet away from the wooden divider, angled towards the doorways in order to capture the approach activity of the children. A second video camera was also angled towards the doorway on the left side of the room about 3ft away from the wooden divider, in case the child turned their back and blocked the other camera's view. Between these two cameras, the crossing and any adjustments on the child's part that may occur on the way to the doorway were captured. The floor was lined with blue tape markers 12 inches apart so that speed and the distance traveled before the child corrects their grip or reorients their body were able to be measured during data-coding. Additionally, black tape was placed on the floor in the shape of a box 8 feet from the center of each door to act as 'start zones'.

Procedure

An experimenter greeted the child and parent(s) outside Maxey Hall, and led them to the Infant Development Lab on the third floor, where all the tasks were completed. The child was given time to become familiar with the lab setting and experimenters while the parent reviewed the consent form and had the chance to ask any questions about the purpose and procedures of the experiment. Once consent was given, the child and parent were then led into the second lab room where the parent took their place on the far side of the wooden divider. Initially, only one doorway was open at a time and the goal bucket stood behind the closed doorway. One experimenter sat behind the camera and tracked the child with the camera as the child walked towards and through a doorway throughout the procedure. The other experimenter handed the child the items to carry through to the other side and actively encouraged the child to stay engaged throughout the trials.

This research procedure involved a quasi-natural situation in which an adult experimenter, a child, and the child's parent partook in a delivery sort of game. The experimenter explained to the child that the idea is to take a tube over to the other side of the doorway and place it in a bucket. In order to encourage the child to play the game and make it more fun, jingle bells ring each time the child places a tube into the bucket. Their parent was visible on the other side of the wooden divider at all times and encouraged the activity (without instructing the child on how to pass through).

Practice Trial Phase. In order to allow the child to get used to the game, the experimenter first ran a few practice trials with small, light, plastic jars for the child to carry through the open doorway and place in the goal bucket. These jars were small enough to fit through either door in any orientation. This was repeated until the experimenter felt that the child was comfortable and ready to move on. The experimenter demonstrated that it is safe and fun to go through the doorways by taking one of the jars through herself. The jars served as control stimuli due to the fact that passing through the apertures while carrying them did not require any adjustment.

Part 1. Following the practice trials, an experimenter positioned the child in the start zone designated for the first doorway and handed a tube or frame to the child with a preference for the correct handle position. Specifically, the experimenter held the tube horizontally and the frame vertically, with the object in front of and at the child's height, and with the handles oriented so that the child could easily grasp the handles. The experimenter sometimes instructed the child to change their grasp if they did not correctly grasp the handles, saying things such as: “grab the handles” or “put one hand here and the other here”.

The experimenter then instructed the child to stand in a ‘start zone’ which was a taped off square area in front of the doorway. This was to guarantee that, for every trial, the children were facing the doorways straight on before they carried the tube through the open doorway to where their parent waited for them. Half of the children were first handed the tube, which was positioned horizontally, then instructed to cross the divide through the tall and skinny door (the short and wide door was blocked off) (Figure 3a). The other half of children were handed the frame (vertically positioned) and had the short and wide doorway open for them to cross (the tall and skinny door was blocked off) (Figure 3b). The first doorway challenge was repeated for 4 trials. The idea was that children had to adjust their grip or their body orientation to successfully pass through the doorway, because the way they were handed the tube would not allow for direct passage (the extension of the tube or frame beyond their body makes them too wide or too tall to fit through).

Figure 3a. A child carrying a horizontally oriented poster tube confronting the challenge of the narrow doorway.

Figure 3b. A child carrying the vertically oriented frame confronting the challenge of the short doorway.

Part 2. Following part 1, the original open doorway was covered and the second doorway opened. Also, the goal bucket was moved behind the newly covered doorway. Children started in the corresponding start zone for the second door, and those who were initially handed the frame vertically, were then handed the tube horizontally and vice versa. They were asked to bring their item through to their parent through either the tall and skinny doorway or the short and wide doorway. This is to counterbalance for any order effects. Again, four trials were attempted.

If any child seemed too shy, uninterested, or overactive to partake in the task after about 8 minutes from the start of the procedure, we stopped data collection and did not include the child in any analyses.

Coding

Video recordings of lab sessions were coded on a variety of measures. A scoring system of 1 to 5 was created to reflect a progression of adjustments and successful crossing of the doorways. On one end of the spectrum, a pass-through score of 1 signifies that the child failed to find a solution to the challenge, gave up, and did not pass through. Scores of 2 and 3 reflect an error being made (colliding with the doorway) before making an adjustment necessary to pass through, with the higher score of a 3 indicating a clean pass-through, post error. A clean pass-through is characterized by crossing through the aperture without the tube or frame touching the inside of the doorway (bumping or sliding along the inner edge). Scores of 4 and 5 were given when no error was made, meaning an adjustment was made before colliding with the doorway, and similarly, the higher score of a 5 indicates a clean pass. Each child was given a pass through score for each trial that they completed on each door. Although many children completed all four trials on both doorway conditions, enough were distracted or became otherwise uninterested before finishing the fourth trial that we decided to only include trials 1 through 3 in our analyses.

Each trial was also given a color zone score to reflect how far from the door they were when they made the adjustment. The “green zone” was designated as the first three feet of space past the start box, and any child who adjusted in this area (with 6 to 9 feet remaining in their walk to the doorway) was given a score of 4. The “yellow zone” was designated as the following three feet of space past the green zone, and any child who adjusted in this area (with 3 to 6 feet remaining in their walk to the doorway) was given a score of 3. The “red zone” was designated as the last three feet of space leading up to the doorway, and any child who adjusted in this area (with 0 to 3 feet remaining in their walk to the doorway) was given a score of 2. A child who failed to adjust before making an error, automatically adjusted in the “black zone” (at the doorway), was given a score of a 1. For computing purposes, we occasionally needed to average the pass through scores or color zone scores of other participants to give a score to a single participant. For instance, if a child only completed two of the four trials on one doorway, we average the third trial scores of the other children in their age group on that doorway so that we were able to give that child a third trial score. This was only necessary for three children.

Each trial was additionally coded for the type of adjustment made by each child. In the process of reviewing the videos, we tallied the dominant adjustment made for each trial. For instance, if a child collided with the tall, skinny doorway and then backed up and turned the tube forward, we would code that as a ‘turning’ adjustment instead of a ‘backing up’ adjustment because the turning adjustment allowed the child to successfully pass through. Aside from the turning adjustment in which a child swiveled one side of the object in front of the other, we found three other dominant adjustments used by children. These were: ducking, tilting, or a change in grasp. An adjustment was coded as ducking when a child moved the object lower to the ground while still holding the object vertically. Some children would do this by ducking just the object and others would bend their knees and duck their body with the object. An adjustment was coded as tilting when a child tilted the object forward or backward so that the top of the object was lower than it was initially. Finally, a child's adjustment would be coded as a change in grasp when the child let go of one or both of the handles in order to reorient their grip on the tube. In this case, the child would often proceed to drag the tube behind them with one hand, or hug the tube close to their body while walking through the opening.

This coding system was not decided upon before data collection began so that we could allow for the inclusion of any creative problem solving strategies. This was congruent with past literature on the ways in which children problem solve. Berger, Adolph, & Lobo, (2005), in a study exploring how children utilize flexible handrails for assistance in locomotion, found that children would often create novel solutions such as stretching the handrail until it is rigid and then move along the walkway with their arms outstretched.

Results

Pass-Through Score

Each child for each trial was given a score as described above. The average scores for each age group and each doorway per trial are displayed in Figure 4a and 4b.

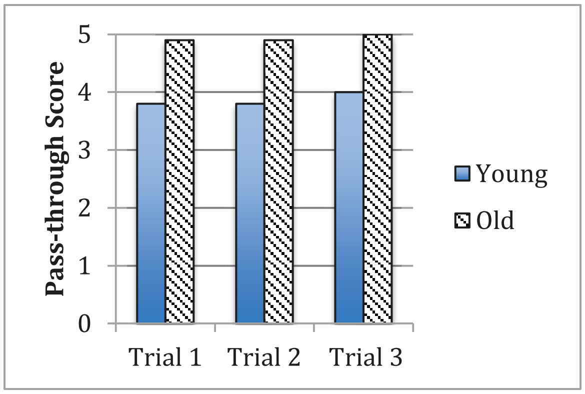


Figure 4a. Average pass-through scores for each age group per the first three trials on the wide, short doorway.

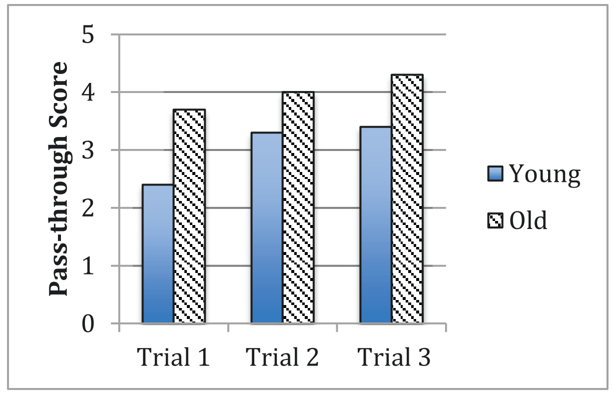


Figure 4b. Average pass-through scores for each age group per the first three trials on the tall, skinny doorway.

To further examine the pass-through scores, we conducted an omnibus 2 (age: young and old) × 2 (doorway: short/wide and tall/skinny) × 3 (trial: 1, 2, 3) mixed ANOVA. The between subjects independent variable was age. The doorway and trial categories were within subjects independent variables. The dependent variable was a pass-through score of 1 through 5. Statistical significance was set at $p < 0.05$, and marginal significance was set at $p = 0.06–0.09$. There was a significant main effect of age, $F(1,17) = 11.12$, $p < .01$. As is seen in Figures 4a and 4b, children in the older age group (28 - 37 months) performed better than the younger age group (15-23 months) on all trials with both doorways. There was also a significant main effect of doorway on pass-through score, $F(1, 18) = 25.64$, $p < .001$; children in both age groups, on all three trials, scored higher (were more successful) on the short/wide doorway. Finally, there was also a significant main effect of trial on pass-through score, $F(1, 36) = 4.74$, $p < .05$; children in both groups scored higher in successive trials on both doorways. There were no significant interactions.

Although the omnibus ANOVA did not show a significant interaction of doorway and trial, due to the pattern of results displayed in Figures 4a and 4b, it seemed that the main effect of trial differences is especially prominent for the tall doorway condition, and possibly for the younger group of children, so we conducted two separate 2 (age: young and old) x 3 (trial: 1, 2, 3) mixed ANOVAs, one for each doorway. The between subjects independent variable was age. The trial number was the within subjects independent variable. The dependent variable in each case was the pass through score of 1 through 5. For the wide/short doorway, there was a significant age effect, $F(1, 17) = 23.09$, $p < .001$; again we saw that older children were more successful than younger children on all trials. On this same doorway, there was no significant effect of trial, $F(2, 36) = 0.53$, $p > .1$; meaning that scores for both age groups did not change substantially over the three trials. However, for the tall/skinny doorway there was both a significant effect of age, $F(1, 17) = 12.53$, $p < .01$, and for trial, $F(2, 36) = 4.83$, $p < 0.05$, older children were more successful on every trial, and both age groups improved their scores over the three trials.

Due to the novelty of the task for the children, we felt it was important to also focus only on trial 1. To compare scores on trial 1 only, a 2 (age group) x 2 (doorway condition) ANOVA also confirmed the significant age effect, $F(1, 18) = 20.12$, $p < .001$, and significant doorway effect, $F(1, 17) = 17.08$, $p < .001$. This reveals that even on the first trial, older children performed better than the younger children on each doorway, and both age groups were more successful in the short/wide doorway condition. Further, we decided to examine the number of children who made an error (a pass-through score of 1, 2 or 3) on trial 1, and those who did not (a pass-through score of 4 or 5) for each doorway condition. For the tall/skinny doorway there were 7 young children and 3 older children who made an error on trial 1, and for the short/wide doorway there were 3 young children and zero older children who made an error on trial 1. For the tall/skinny doorway, 1 young child and 7 older children did not make an error on trial 1, and for the short/wide doorway there were 4 young children and 10 older children who did not make an error on trial 1. Fisher exact probability test revealed significant differences for the age groups and their success on trial 1 for both doorways, $p = 0.023$ and $p = 0.05$ for the tall/skinny and short/wide doorways, respectively. This shows that older children not only scored higher, but also made significantly fewer errors than the younger age group on their first trial on both doorways.

Advanced Adjustment

After finding that the older age group was significantly less likely to make errors in comparison to the younger age group, we decided to look within the older age group of children to see if they made their adjustment further in advance of the doorways as the trials progressed. For this analysis, we utilized our color zone scores (described above), and used only children who did not make an error (earned a pass-through score of a 4 or 5, because children who made an error always made their adjustment in the black zone) on trials 1, 2 or 3. Within the older group of children, 8 children never made an error on the short/wide doorway and 7 children never made an error on the tall/skinny doorway. The average color zone scores for this subset of participants are shown below in Figures 5a and 5b.

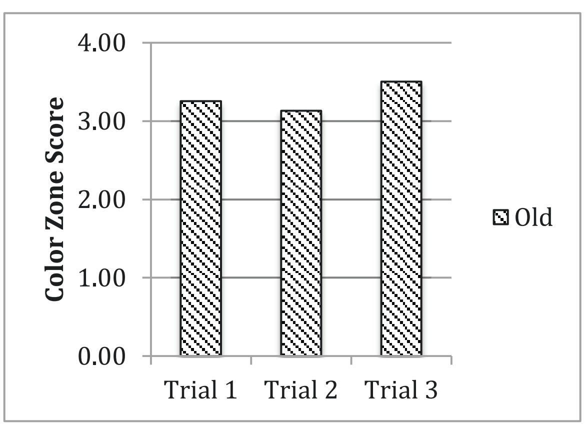


Figure 5a. Average color zone scores for the older children who did not make an error on any trial on the short, wide doorway.

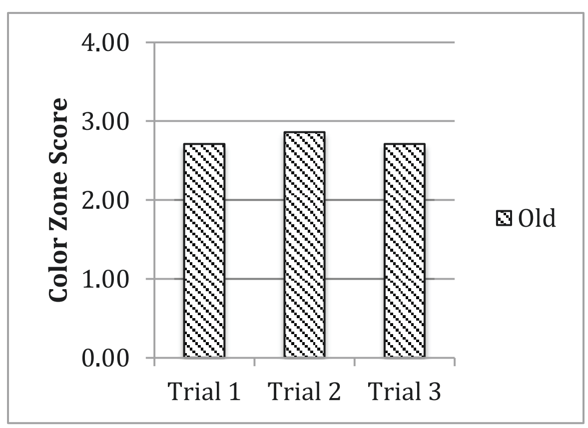


Figure 5b. Average color zone scores for the older children who did not make an error on any trial on the tall, skinny doorway.

Using only these children's data, we ran two one-way ANOVAs using the color zone scores on the scores of the first three trials. One ANOVA was run for each doorway, neither yielded a significant effect of trials. As shown in figures 5a and 5b, the color zone score of the older children's color zone scores hovered around 3.25 for the wide doorway, and 2.75 for the tall doorway. The lack of significance indicates that children were not consistently making their adjustments any earlier or any later in their walk towards the doorways as the trials progressed.

Strategy

Regardless of where the child was when they adjusted (in the start box, mid-walk, or at the doorway), type of adjustment was recorded to look at differences between age group and doorway condition. To illustrate these results, we created eight graphs (Figures 6a-9b) to show the percentage of children in each age group who made each adjustment, for each doorway.

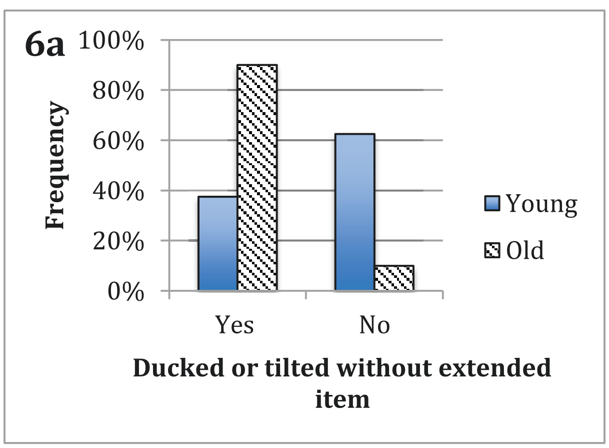


Figure 6a represents adjustments on the control trial for the short, wide doorway when crossing with a non-extended object.

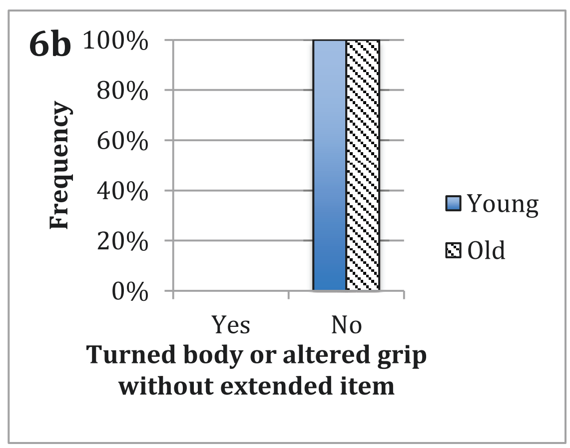
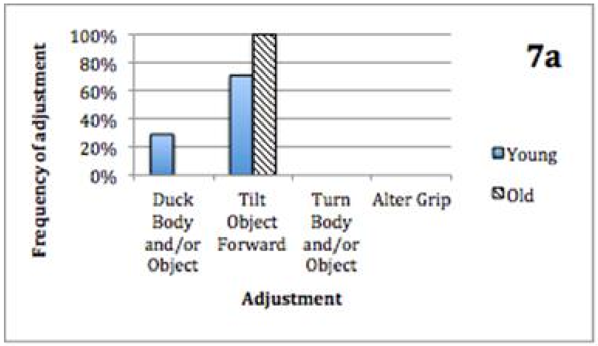


Figure 6b represents adjustment strategies used on the tall, skinny doorway when crossing with a non-extended object.

Within the 4 types of adjustments we saw children make, tilting the object and ducking the object were only appropriate for the short/wide doorway. These adjustments would not help get through the tall/skinny doorway and instead, turning the object or altering grip were most appropriate.

As illustrated by Figures 6a and 6b, except for the fact that some children, especially older (taller) ones, ducked when going through the short doorway without an extended item, most children did not make any of the target adjustments when carrying a non-extended object through; the adjustments were primarily made when a navigational problem was either anticipated or experienced. As is seen in Figures 7a through 9b, all children on all trials made an appropriate adjustment for the doorway they were travelling through. That is, children generally did not turn or re-grip the object when crossing through the short doorway, and they never ducked or tilted the object to go through the tall doorway. One child on one wide door trial changed his grasp on the vertical object. However, this was still an appropriate adjustment because the particular re-grasping strategy the child used changed the orientation of the frame and allowed him to pass through successfully.

With these data, we ran a McNemar test for change to analyze the number of times children tailored their adjustment strategy to fit the given challenge on trial 1. For the McNemar test, we paired the two appropriate adjustments for the horizontal challenge (tall/skinny doorway: turning/altering grip), and the two appropriate adjustments for the vertical challenge (short/wide doorway: tilting/ducking) to create two categories of potential adjustments children might use on one or both doorways to confront the two different challenges. Any children who turned or altered their grip on the object for both doorways, as well as any children who ducked or tilted the object forward for both doorways was left out for this test, as these two groups do not represent any “change’



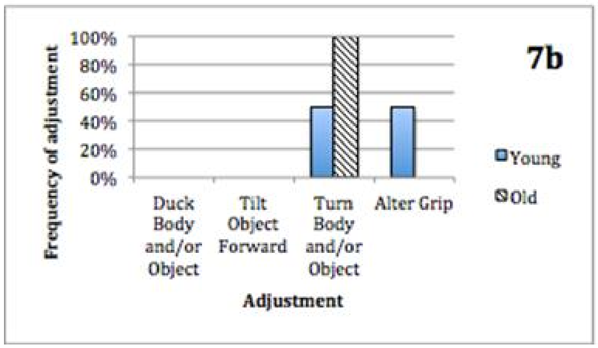
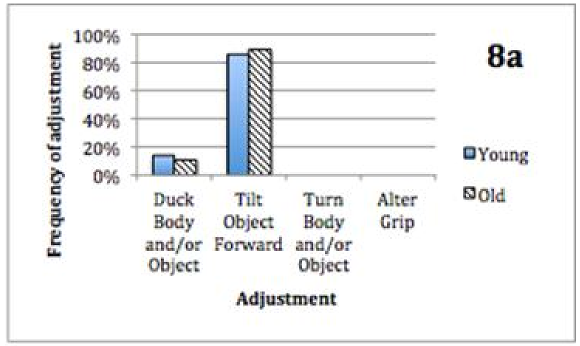


Figure 7a. Frequency of adjustment strategy used on trial 1 of the short, wide doorway, divided by age group.
Figure 7b. Frequency of adjustment strategy used on trial 1 of the tall, skinny doorway, divided by age group.



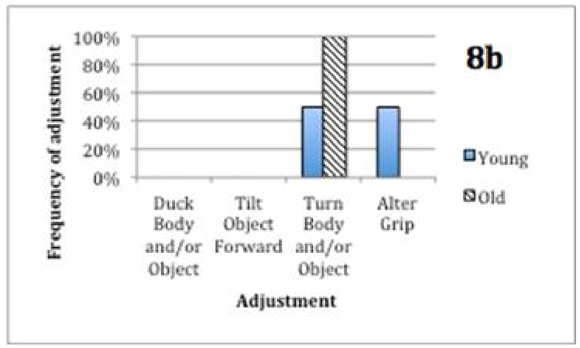
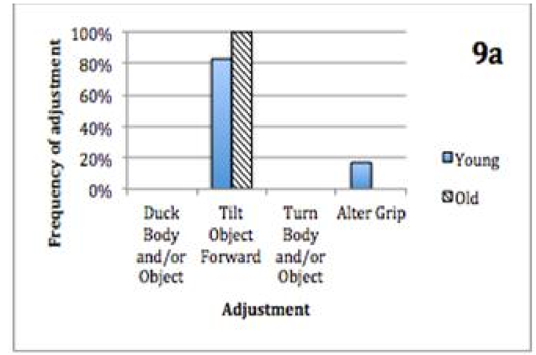


Figure 8a. Frequency of adjustment strategy used on trial 1 of the short, wide doorway, divided by age group.
Figure 8b. Frequency of adjustment strategy used on trial 1 of the tall, skinny doorway, divided by age group.



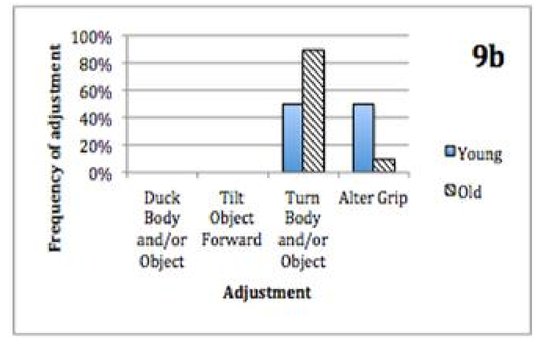


Figure 9a. Frequency of adjustment strategy used on trial 3 of the short, wide doorway, divided by age group.
Figure 9b. Frequency of adjustment strategy used on trial 3 of the tall, skinny doorway, divided by age group.

across the distinct challenges (in our study, none of the children fit into these two categories). The remaining groups who were analyzed for change in strategy in the McNemar test were those who inappropriately used a horizontal adjustment for the vertical door, and those who inappropriately used a vertical adjustment for the horizontal door ($N = 0$), contrasted with those who made adjustments tailored appropriately for each doorway ($N = 16$). All 16 children who completed both doorway conditions appropriately adjusted for each doorway, $p < 0.01$. This illustrates that all children were making specific adjustments based on the doorway they were going through (ie. tilting or ducking only on the wide/short doorway and turning or re-grasping only on the tall/skinny doorway).

Figures 7a-9b show that for the wide door, both age groups predominantly tilted the frame forward to cross through the aperture. However, for the tall doorway, the older children all turned the tube ($N = 10$), while half of the younger children turned ($N = 4$) and half of the younger children altered their grip ($N = 4$). To test for differences between the two age groups in terms of the type of adjustment made on the first trial of the tall/skinny doorway, we ran a Fisher exact probability test, $p = 0.02$. This test confirmed that older children were more likely to make a turning adjustment on the tall door than the younger children.

Discussion

Pass-through score

Our results show that our hypothesis regarding age differences in the problem solving and planning abilities of young walkers was confirmed. On average, older children had higher pass-through scores than the younger group on every trial for both doorways. This result is not surprising, due to the fact that the year of long-term development that occurs between our two age groups (between about 2 and 3 years old) involves countless opportunities for experience walking, carrying and combining those challenges while crossing through apertures. Previous literature on infant development has demonstrated many times that skills and behaviors are developed in the context of experience (Adolph, et al., 2012; Berger, Adolph, & Lobo, 2005; Franchak & Adolph, 2012). The thousands of steps that children take every day, in combination with some of the more complex locomotor challenges that they face in their varied environment no doubt contribute to the problem-solving and planning abilities that were demonstrated by the older age group when confronted with the dilemma presented by the current study's design. If this study were to be continued, we would expect to see that if given a year to continue developing and gaining long-term experience, the younger group would then attain comparable scores to the older group.

One potential limitation with the scoring system that was created for this scenario is that a score of a 4 and 5 were very similar in practical terms of success. For the items that the children were asked to carry, bumping the inner edges of the doorways on the way through made little to no difference to their task. Similarly, scores of 2 and 3 were nearly the same in terms of final success. However, the difference between a score of a 1, 2 or 3 (collided prior to adjustment) when compared to a 4 or 5 (no error prior to collision) reflects a clear-cut difference in overall success. The significant difference we saw here confirmed our hypothesis that the older children would be successful at crossing through the doorways even without needing an initial collision to prompt an appropriate adjustment, whereas the younger children's performance reflects more of a "post hoc" adjustment.

Due to a lack of relevant research, we were originally unable to form hypotheses regarding differing success on the separate doorway challenges. Our results showed a clear difference in success across age groups for the two doorways; every child was more successful on the short/wide doorway. There are many potential explanations for this difference in success. It could be due to the nature of our stimulus, in that our task requires the child to look straight ahead through the doorway to their parent waiting on the other side. Looking straight ahead through the opening while crossing with the vertically held frame would keep the low-hanging barrier in the child's immediate view in a way that is clearly juxtaposed with the size and orientation of the vertically held item. However, looking through the doorway while carrying the horizontal tube does not necessarily maintain focus on each of the overhanging sides of the poster tube when matched with the tall/skinny doorway. It is also possible that children are more perceptually sensitive to low hanging barriers due to the potential high cost of an error: hitting their head. In our scenario, the apertures were tall and wide enough so that limb-hitting was not a real risk, however the top edge of the short doorway was fairly close to their heads, making it common for them to duck as a precaution. Their exaggerated avoidance of this low barrier was very different than their behavior on the tall/skinny doorway where they would rush through without any hesitation or caution (in the case of younger children, often without an adjustment, either). Another potential limitation of the differing items is that in the narrow opening condition, an error stopped them in their tracks due to the nature of the mismatch between size of the object, orientation of the object and aperture. In the short doorway condition, occasionally, even if an error was made, the child would hesitate then keep walking, with the top ledge of the doorway then guiding the frame into an adjusted position (tilted back) that allowed continuing on. In the future, this study could be improved by creating an even taller vertical item to carry through that would make as exaggerated a consequence as the tall/skinny doorway when an error was made.

We hypothesized that we would see evidence of improvement through the short-term experience of executing four trials. Even though many children only completed three of the four trials, our analyses suggested trial effects for all children on both doorways, specifically, that they improved their pass-through score on each successive trial. This hypothesis was partially confirmed. Although we did find an overall significant trial effect across age and doorway, it was much more prominent for the more difficult tall/skinny doorway condition than the short/wide condition. This was true for both ages. One possible reason that the trial effect is more visible on the tall door relates back to the demonstrated doorway effect. Because both age groups scored better on the short/wide door, there was less room for improvement in scores across trials. We may even be seeing a ceiling effect within the older group of children on the short/wide doorway; nearly all of these children received perfect scores on their first trial. Another possible reason for the trial effect that was especially strong for the tall/skinny condition is that as we mentioned above, an error for this condition was much more obvious, frustrating, limiting, and possibly motivating effortful change to avoid getting stuck again.

Advanced adjustment

We hypothesized that children who never made an error might make their adjustment further and farther in advance on subsequent trials because these children would recognize an appropriate solution on their first trial and then use it earlier on subsequent trials. However, this was not supported; children did not make their adjustments further in advance of the doorways in subsequent trials. Upon greater reflection, we found that this is not necessarily an unexpected result, as an earlier adjustment does not exactly equate to more cognition. It is possible and quite likely that these children recognize their appropriate adjustment on the first trial, but are not making that adjustment on subsequent trials until 'just in time' when it is necessary to do so. This is because we designed the stimulus to prime a hand positioning that requires an adjustment in order for the child and object to pass through successfully. Thus, the adjustments that the children must make to be successful in passing through are less comfortable to sustain. So, children that make their adjustments much earlier than necessary would need to hold the object in a less comfortable position for a longer amount of time. Consequently, making an adjustment 8 feet from the doorway, for instance, is neither an easier solution nor will it allow a more successful pass through than adjusting 3 feet from the doorway.

Strategy

Through comparison with the control trials in which children carried objects that were smaller than their bodies, we can conclude that the errors and the adjustments the children made during the experimental trials were due to the inconveniently shaped objects they carried on the experimental trials. All children passed through both doorways easily in the control trials and with no adjusted behaviors, with the exception that some children (3 young, 9 old) ducked unnecessarily when walking through the short/wide doorway (Figure 6a). We suspect this is due to the differences in height as the older children are taller and ducked to avoid the potential of hitting their head (even though the doorway was tall enough so they did not need to). No children turned their body when going through the tall/skinny doorway while carrying the small object (Figure 6b).

As Figures 7a-9b show, all children in both age groups made only appropriate adjustments (tilting or ducking for the short/wide doorway, turning or changing grasp for the tall/skinny doorway) on all three trials and on both doorways. That is, all children tailored their adjustments to the particular doorway, showing sensitivity to the affordances of their body, the object, and the size and shape of the opening. Furthermore, even the young children who more frequently made errors never needed to use a system of trial and error to find an appropriate adjustment; upon making an error, they straight away chose a unique and appropriate solution to confront the challenge. This suggests that the process of committing an error was sufficient for the children to gain more insight into the nature of the problem to solve it appropriately and immediately. For example, when a child collided the tube with the sides of the narrow doorway they were able to identify that those overhanging edges of the tube were blocking their passage through the doorway. This prompted an adjustment strategy that aimed to eliminate those specific barriers, i.e. moving the sides of the tube out of the way of the sides of the doorway.

However, between the age groups, we do see a preference for one adjustment over another. Specifically, on the tall/skinny doorway, the older children used the turning adjustment more frequently than the younger children. It is important to mention that in our study, any adjustment that allows both the child and object to pass is considered successful. However, not all adjustments are equally successful when carrying objects in real life situations. We hypothesize that tilting or turning are more mature types of adjustments because they do not impact one's walk. A ducking adjustment is more disruptive of one's walk because it requires one to crouch for an extended period of time while walking. Similarly, a re-grasping adjustment in which one lets go of one hand on the object and hugs the object to their body disrupts their walk because the long object will now get in the way of their feet. Although the ducking and re-grasping adjustments that mostly the younger children made were appropriate for the confines of our study, the older children exhibited more mature strategies (tilting and turning) in terms of easing the difficulty of carrying while walking.

General Comments

The current study provides evidence to add to a growing body of literature showing that even young, relatively inexperienced, preverbal children exhibit impressive levels of embodied cognition. Previous research has shown that children are able to find solutions when locomoting with the assistance of non-rigid handrails, when navigating down and up steep slopes, and passing through apertures that were smaller than their body (Adolph, Eppler, & Gibson, 1993; Berger, Adolph, & Lobo, 2005; Franchak & Adolph, 2012). Likewise, in the challenging carrying scenarios created for this study, all of the children were able to solve the problems, and most even showed improvement over the short-term experience of executing consecutive trials. We see in the fact that these children did not blindly guess for an adjustment that might help them solve the problem; they tailored their adjustments to the specific constraints of the challenge at hand, changing their strategy appropriately when the situation changes. With age, and undoubtedly with experience, these children not only made these appropriate adjustments more smoothly and efficiently, but also further in advance to avoid any error. This is important because it shows that children at this older age (3 year old) are able to not only accurately perceive problems, but also can foresee them and form and execute a motor plan to successfully confront them. This supports the findings of past research by McCarty et al. (1999) in which 19-month-old infants were found to show earlier signs of plan formation and execution in regard to accurately positioning spoons to complete a task.

The success of our subjects is likely grounded in the multitude of steps that children of this age take every day, often in an attempt to confront the countless motor challenges they face in their ever-expanding environment. As we all know, life's locomotor challenges continue to get more complicated past 3 years of age. Further studies investigating embodied cognition, problem-solving and strategic locomotion could reflect these complications by adding layers of difficulty to the setup we created. This could be in the form of asking children to carry items that are unevenly weighted, adding a balance challenge, for instance. Items could be made to be too tall *and* too wide to fit through the openings without an adjustment in a third plane of movement. In our study, any adjustment strategy was valid if it resulted in getting both the child and the object to the other side of the doorway. However, some of the strategies that our participants used would be unreasonable in real life or with objects that had more specific movement constraints. A future study could involve items that eliminate possible adjustment strategies; for example a tray with water or food items resting on it would eliminate the grip adjustment strategy (drop one handle, then drag or hug the item through the doorway) that we saw so often with the older children.

In conclusion, the strategic planning skills that the children in this study demonstrated are built through short and long-term experience in varied environments that demand understanding the limits and capabilities of ones' body. The combination of independent locomotion, carrying, and unusually sized apertures provides a window into how perception, cognition and action dynamically work together in children to produce flexible solutions to new motor challenges.

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