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# Flexible recalibration of perception and action in children and adults

Christine Julia Ziemer
*University of Iowa*

# FLEXIBLE RECALIBRATION OF PERCEPTION AND ACTION IN CHILDREN AND ADULTS

by

Christine Julia Ziemer

<u>An Abstract</u>

Of a thesis submitted in partial fulfillment of the
requirements for the Doctor of Philosophy degree
in Psychology in
the Graduate College of
The University of Iowa

July 2012

Thesis Supervisor: Professor Jodie M. Plumert

# ABSTRACT

We conducted eight experiments to examine how manipulating perception vs. action during walking affects perception-action recalibration in real and imagined blindfolded walking tasks. Participants first performed a distance estimation task (pretest), and then walked through an immersive virtual environment on a treadmill for 10 minutes. Participants then repeated the distance estimation task (posttest), the results of which were compared to their pretest performance. In Experiments 1a, 2a, and 3a, participants walked at a normal speed during recalibration, but the rate of visual motion was either twice as fast or half as fast as the participants' walking speed. In Experiments 1b and 2b, we tested 12-year-old children in the same recalibration task as 1a and 2a. In Experiments 1c, 2c, and 3b, the rate of visual motion was kept constant, but participants walked at either a faster or a slower speed. During pre- and posttest, we used either a blindfolded walking distance estimation task or an imagined walking distance estimation task. Additionally, participants performed the pretest and posttest distance estimation tasks in either the real environment or in the virtual environment. With blindfolded walking as the distance estimation task for pre- and posttest, we found a recalibration effect when either the rate of visual motion or the walking speed was manipulated during the recalibration phase. With imagined walking as the distance estimation task, we found a recalibration effect when the rate of visual motion was manipulated but not when the walking speed was manipulated in both the real environment and the virtual environment. Neither blindfolded walking nor imagined walking yielded significant results when 12-year-old children were tested. Discussion focuses on how spatial updating processes operate on perception and action and on representation and action.

Abstract Approved: ________________________________________
Thesis Supervisor

________________________________________
Title and Department

________________________________________
Date

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Iowa City, Iowa

CERTIFICATE OF APPROVAL

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PH.D. THESIS

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This is to certify that the Ph. D. thesis of

Christine Julia Ziemer

has been approved by the Examining Committee for the thesis requirement for the Doctor of Philosophy degree in Psychology at the July 2012 graduation.

Thesis Committee: ___________________________________
Jodie Plumert, Thesis Supervisor

___________________________________
Joseph Kearney

___________________________________
John Spencer

___________________________________
Susan Cook

___________________________________
Shaun Vecera

To my parents and grandparents for their never-ending support and love

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We conducted eight experiments to examine how manipulating perception vs. action during walking affects perception-action recalibration in real and imagined blindfolded walking tasks. Participants first performed a distance estimation task (pretest), and then walked through an immersive virtual environment on a treadmill for 10 minutes. Participants then repeated the distance estimation task (posttest), the results of which were compared to their pretest performance. In Experiments 1a, 2a, and 3a, participants walked at a normal speed during recalibration, but the rate of visual motion was either twice as fast or half as fast as the participants' walking speed. In Experiments 1b and 2b, we tested 12-year-old children in the same recalibration task as 1a and 2a. In Experiments 1c, 2c, and 3b, the rate of visual motion was kept constant, but participants walked at either a faster or a slower speed. During pre- and posttest, we used either a blindfolded walking distance estimation task or an imagined walking distance estimation task. Additionally, participants performed the pretest and posttest distance estimation tasks in either the real environment or in the virtual environment. With blindfolded walking as the distance estimation task for pre- and posttest, we found a recalibration effect when either the rate of visual motion or the walking speed was manipulated during the recalibration phase. With imagined walking as the distance estimation task, we found a recalibration effect when the rate of visual motion was manipulated but not when the walking speed was manipulated in both the real environment and the virtual environment. Neither blindfolded walking nor imagined walking yielded significant results when 12-year-old children were tested. Discussion focuses on how spatial updating processes operate on perception and action and on representation and action.

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# CHAPTER 1: INTRODUCTION

As we locomote through the world, we constantly experience the relationship between our rate of physical movement and the rate of visual motion. For example, if we walk quickly down a sidewalk we experience a faster rate of visual motion than if we walk slowly. Over time, this vast experience with the regularities between perception and action allows the system to build up expectations about how a given amount of movement will lead to a given amount of distance travelled. The statistical regularity between the amount of movement and the distance travelled is only altered through mechanical devices such as moving sidewalks in airports. In such cases, the amount of walking produces a greater amount of distance travelled than we normally experience. With enough experience on a moving sidewalk, people should recalibrate, or adapt to a new relationship between perception and action. In fact, several studies have shown that recalibration does occur, even after only 10 minutes of experience with an altered relationship between perception and action (e.g., Mohler, Thompson, Creem-Regehr, Pick, Warren, Rieser, & Willemsen, 2004; Mohler, Thompson, Creem-Regehr, Willemsen, Pick, & Rieser, 2007; Proffitt, Stefanucci, Banton, & Epstein, 2003; Rieser, Pick, Ashmead, & Garing, 1995; Withagen & Michaels, 2002). Beyond these demonstrations of recalibration, however, relatively little is known about the processes that underlie the recalibration of perception and action. Here, we further examine how spatial updating processes operate on perception and action and on representation and action.

Coupling of Perception, Action, and Representation

According to Rieser and Pick (2007), perception, action, and representation are coupled together in an organized system that allows us to act adaptively whether perceiving (e.g., looking or listening) or representing (e.g., visualizing or imagining) the environment around us. Under normal circumstances, we use perception to guide action. Thus, if we want to pick up an object on the other side of a room, we simply look at the object while walking over to the location. This system of on-line control is highly accurate and efficient, and likely governs much of our daily interactions with objects. Under other circumstances, however, we can use representation to guide action. For example, even without vision (due to blindness or darkness), we can walk over to pick up an object on the other side of a room (Rieser, Guth, & Hill, 1986). This system of control relies on the coupling of action and representation, involving the coordination of motor actions with spatial knowledge.

Rieser and Pick (2007) hypothesize that similar processes operate on both perception-action coupling and representation-action coupling. In particular, when we walk with vision, we automatically keep track of the kinematics of our stepping (i.e., step rate and step length) relative to the rate of visual motion to update our position relative to the surrounding environment (Loomis, Da Silva, Fujita, & Fukusima, 1992). This process is referred to as spatial updating. Rieser et al. (1995) posit that the coupling of perception and action can account for the coupling of representation and action. In other words, as we learn the relationship between our actions and our perception under normal conditions (e.g., with visual feedback), we are able to relate this experience to our representation of space in order to act adaptively when conditions require us to rely on representation.

Specifically, when people walk without vision, spatial updating processes operate on representations of the surrounding environment, allowing people to know where they are in relation to the surrounding environment. As a result, they are able to walk without vision to targets up to 30 m away fairly accurately (Farrell & Thomson, 1998, 1999).

When the normal link between rate of physical movement and visual movement is altered (as in the moving sidewalk example), spatial updating processes cause people to recalibrate the link between perception and action. We can measure this change in the perception-action-representation relationship in tasks where people rely on their representation of the environment while performing an action task without vision. Tasks such as blindfolded walking or blindfolded imagined walking to previously seen targets have been used to probe changes in the perception-action-representation system (e.g., Kunz, Creem-Regehr, & Thompson, 2009; Mohler et al., 2004; Mohler et al., 2007; Rieser et al., 1995). In these types of tasks, participants rely on their representation of space coupled with their recalibrated sense of how much action it takes to reach the target. Participants overshoot the target if they have experienced more walking in order to cover a given distance, and they undershoot the target if they have experienced less walking to cover a given distance.

## Manipulating the Rate of Visual Motion to Produce Recalibration of Perception and Action

Several researchers have demonstrated the flexibility of perception-action recalibration in laboratory settings (e.g., Mohler et al., 2004; Mohler et al., 2007; Proffitt et al., 2003; Rieser, et al., 1995; Withagen, & Michaels, 2002). The perception-action relationship is usually manipulated by altering the rate of the environmental visual movement (i.e., faster or slower) in relation to the participant’s walking speed. A common task used to measure change in the perception-action-representation relationship is blindfolded walking in which participants attempt to walk blindfolded to previously viewed targets both before and after the recalibration experience. Blindfolded walking has been shown to be a reliable way to measure participants’ representation of distance (Farrell & Thomson, 1998, 1999; Rieser, Ashmead, Talor, & Youngquist, 1990).

In the original recalibration study, Rieser et al. (1995) found that people recalibrated the link between perception and action after a brief period of altered covariation of biomechanical activity and visual motion. Participants completed a pre- and posttest in which they viewed targets at 8m away and then attempted to walk to them with their eyes closed. Between the pre- and posttest, participants experienced a “rearrangement,” or adaptation, phase in which they walked at a constant speed on a motor-driven treadmill that was being pulled by a tractor at a faster or slower speed. Participants therefore experienced visual motion at either a faster or slower rate than the biomechanical speed at which they were walking. Using a blindfolded walking task, Rieser et al. (1995) found that participants who experienced slower visual motion walked past the target during the posttest, whereas participants who experienced faster visual motion stopped short of the target during posttest. These results indicate that the participants learned the new relationship between visual motion and walking speed during the adaptation period. When the visual motion was fast relative to their speed of walking, participants learned that they traveled more distance with each step than before, and when the visual motion was slow relative to their speed of walking, they learned that they traveled less distance with each step.

Other researchers have replicated Rieser et al.'s (1995) recalibration effect using a treadmill in a virtual environment during the adaptation phase (e.g., Mohler et al., 2004; Mohler et al., 2007; Proffitt et al., 2003; Withagen & Michaels, 2002). The use of a virtual environment is helpful for eliminating potential methodological problems with Rieser et al.'s (1995) study such as a raised eye height and the view of the tractor while being pulled on a treadmill. In Mohler et al.'s study (2004, 2007), participants first performed a pretest in a real hallway which involved nine trials of walking blindfolded to targets at different distances (6, 8, and 10 m). Following the pretest, participants walked on a treadmill in a virtual environment that was modeled after the real hallway. During the adaptation phase in the virtual environment, visual motion was adjusted to be either faster, slower, or the same as the speed of walking. Following the adaptation experience, participants performed a posttest that was identical to the pretest. They found that participants who had experienced slower visual motion in the virtual environment overshot the target distances during posttest relative to pretest by 11% while participants who had experienced faster visual motion undershot the same distances at posttest relative to pretest by 6%. It is important to note that the recalibration rates found in these studies are not comparable in size to the relationship established during the adaptation experience. Although the rate of visual motion may be twice as fast or half as fast as participants' walking speed during adaptation, the recalibration effects observed during posttest are much more subtle.

To date, research on perception-action recalibration has only attempted to produce recalibration by changing the rate of visual motion during adaptation while holding walking speed constant. No studies have examined whether recalibration occurs to the same extent when the perception-action relationship is altered by changing the speed of physical movement while keeping the rate of visual motion constant. In order to better understand how altering the link between perception and action produces recalibration, it is important to determine whether we can experimentally produce recalibration through manipulating different components of the perception-action system. If people are sensitive to the relationship between physical movement and visual motion, then changing this relationship either through manipulating physical movement or through manipulating visual motion should produce recalibration.

## Recalibration of Perception and Action Using Blindfolded Walking and Imagined Walking Tasks

As discussed above, recalibration has typically been studied via a blindfolded walking task during pre- and posttest. This task is considered the gold standard for studying recalibration of perception and action since it allows for a fairly direct test of whether people's sense of the amount of movement required to travel to a previously seen target has changed based on a recalibration experience. Presumably, blindfolded walking engages spatial updating processes based on the tight coupling between perception, action, and representation.

More recently, imagined walking has been used to assess distance perception in both real and virtual environments (Decety, Jeannerod, & Prablanc, 1989; Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010; Kunz et al., 2009; Plumert, Kearney, Cremer, & Recker, 2005; Ziemer, Plumert, Cremer, & Kearney, 2009). The basic task is identical to blindfolded walking to targets, except that participants imagine walking to targets while standing in place. Kunz et al. (2009) recently tested recalibration of perception and action using this imagined walking task. Participants walked on a treadmill through a large-screen virtual environment during adaptation, but made imagined walking distance estimates during pre- and posttest. Participants started a stopwatch when they imagined themselves beginning to walk to the target and stopped it when they imagined reaching the target (without ever looking at the stopwatch). When estimating the amount of time it would take them to walk to targets at posttest relative to pretest, participants in the slower visual motion condition overshot the target relative to pretest by 15% and participants in the faster visual motion condition undershot the target relative to pretest by 14%. Kunz et al. (2009) concluded that recalibration is similar when tested with an imagined walking task as compared to the standard blindfolded walking task.

Although imagined walking is similar to blindfolded walking, there are important differences between these two tasks that warrant further investigation with regard to their use in measuring recalibration of perception and action. One potentially important difference is the similarity of the distance estimation task to the recalibration experience. Clearly, the blindfolded walking task is more similar to what participants experience during the recalibration phase than is the imagined walking task. Although both blindfolded and imagined walking involve making distance estimates without vision, participants are physically walking through space during blindfolded walking, whereas they are imagining walking through space (while standing still) during the imagined walking task. Since the spatial updating processes used in the imagined walking task are less similar to the recalibration experience than are the spatial updating processes used in blindfolded walking, it is possible that we may not see recalibration effects as strongly when using an imagined walking task.

This argument rests on the idea that imagined walking is less grounded in the environment since it does not involve the same proprioceptive feedback (i.e., joint motion, acceleration) that people experience when walking through the environment while blindfolded. Previous research has shown that people are able update their spatial position fairly accurately when walking through space without vision (Rieser et al., 1990; Rieser et al., 1986; Thompson, 1983). However, it is more difficult for people to imagine themselves in a different orientation or location other than the one they know themselves to be in (Farrell & Thompson, 1998; Rieser et al., 1986). Rieser explains this difference by suggesting that spatial updating processes are automatic when coupled with physical movement, but imagining movement and the corresponding spatial updating requires more cognitive effort (Rieser, 1989; Rieser et al., 1986). This discrepancy between real and imagined movement suggests that it may be harder to see a recalibration effect with the imagined walking task.

## Recalibration of Perception and Action Across Development

Another factor that may influence recalibration is the organism itself. In particular, do the same processes that occur in the moment for these types of recalibration tasks in adults also apply to children in different stages of development? Rieser et al. (1995) attribute calibration to a learned covariation of perception and action. This covariation obviously changes with things such as growth and increased practice, allowing children to recalibrate as their bodies and skills change over time. At present, however, it is not known whether children are able to notice a change in the learned covariation between perception and action. It is possible that children would be quite adept at recalibrating since their bodies are growing and changing at a rapid rate. However, they also have had less experience with the learned covariation between perception and action, which may lead them to be less skillful at learning new perception-action relationships.

As discussed earlier, research to date on the recalibration of perception and action has manipulated the rate of visual motion while keeping walking speed constant. In extending this paradigm to children, it is first important to determine how adept children are in using optic flow cues to update their spatial location as they move through an environment. According to James Gibson (1979) optic flow allows us to discern our relative velocity of movement as we move through a rigid environment. Therefore, the ability to perceive and use optic flow is crucial for the spatial updating process. Eleanor Gibson suggested that the use of optic flow does not need to be learned through exploration, but is an automatic product of the perceptual competence that infants possess at a very young age (Gisbson, 1988; Banks, 1988). Higgins, Campos, and Kermoian (1996) demonstrated that infants with self-locomotion ability as young as 7-9 months old respond to changes in optic flow in order to control their posture in a moving room. Therefore, young children should already possess the ability to use visual motion information in order to recalibrate perception and action.

Although there have been no recalibration studies done with children to date, work by Adolph and Avolio (2000) and Garciaguirre, Adolph and Shrout (2007) has shown that new walkers are quite adept at noticing changes to their body and altering their actions in accordance with these changes. Garciaguirre et al. (2007) loaded 14-

month-old infants with weights that were 15% of their body weight. The weight raised the children's center of mass, making it harder for them to keep their balance while walking. In response to the weights, toddlers altered their gait and footfall patterns to cope with their impaired balance. Similarly, Adolph and Avolio (2000) fitted 14-month-old babies with lead-weighted vests that were 25% of their body weight in order to see how the infants adapted their locomotion to account for this weight change while attempting to walk down slopes of different degrees of steepness. They found that the toddlers did in fact change their action decisions in accordance with their now impaired balance abilities. Infants resisted walking down a slope that was too steep for them to successfully complete without falling when wearing the weighted vest. Some of the exact same slopes that infants resisted with the lead-weighted vests they had successfully walked down when unhindered by the vest.

Since Adolph and Avolio (2000) alternated between lead-weight vests and feather-weight vests by trial, infants needed to calibrate quickly at the beginning of each trial in order to determine which slopes were crossable. They found that small exploratory actions, such as rocking a foot on the edge of the slope or swaying slightly, was all that was required for infants to calibrate to their altered body dimensions. However, calibration was not perfect or complete. Toddlers tended to overestimate their abilities on slopes that were slightly beyond their abilities when wearing the lead-weighted vests, often resulting in a fall. This study demonstrates infants' ability to adapt to changes in the moment, but does not examine the carry-over effect of this adaptation once the adaptation period is over (i.e., the vests are removed). Therefore, it is still unknown whether children show a recalibration effect after adapting to changes in perception-action coupling. If Adolph and Avolio (2000) used the format of the adult recalibration studies (pretest, adaptation, posttest), would infants exhibit altered performance on slopes during posttest if they had experienced lead-weighted vests during adaptation?

The evidence above suggests that infants and toddlers are able to use both changes in the rate of visual motion and changes in their physical dimensions to guide their actions. However, we still don't know if children recalibrate the link between perception and action after an experience that mismatches the two. In the current investigation, we examined whether 12-year-old children recalibrate to the same extent as adults after experiencing an adaptation phase with a mis-match of perception and action. We chose 12-year-old children for this task as children at this age are able to use a treadmill adequately and we have observed similarities between 12-year-old children and adults in distance estimation tasks in previous research (Plumert et al., 2005).

<u>Recalibration of Perception and Action in Real and Virtual Environments</u>

One final element that might influence the extent to which people exhibit recalibration of perception and action is the environment in which the pre- and posttest tasks take place. We have vast amounts of experience with the relationship between our walking speed and distance traveled in the real world. Given this, recalibration studies to date have tested perception-action recalibration by having people estimate distances in the real world before and after the recalibration experience (even when the recalibration experience occurs in a virtual environment). At present, however, little is known about how people recalibrate perception and action in virtual environments.

Many studies have found that people significantly underestimate distances in virtual environments, suggesting that perception is more malleable in virtual environments (Nguyen, Ziemer, Grechkin, Chihak, Plumert, Cremer, & Kearney, 2011; Swan, Jones, Kolstad, Livingston, & Smallman, 2007; Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, & Beall, 2004; Witmer & Kline, 1998; Witmer & Sadowski, 1998). In short, people misjudge how much movement is required to travel a given distance in a virtual environment; they systematically underestimate the amount of movement required to reach the desired destination. One possible explanation for this may be that virtual environments appear compressed. Research has shown that giving participants time to become familiar with walking to targets in the virtual environment greatly increases their accuracy in distance estimation tasks (Interrante, Anderson, & Ries, 2006; Waller & Richardson, 2008). Due to the relative unfamiliarity of the virtual environment used in recalibration studies, participants may rely more heavily on the perception-action relationship learned during the recalibration phase. Therefore, one might expect a stronger recalibration effect in a virtual environment than in the real environment.

## The Present Investigation

The goal of the present investigation was to better understand the spatial updating processes that operate on perception and action and on representation and action. With regard to spatial updating processes operating on perception and action, we were especially interested in determining whether the link between perception and action can be recalibrated by altering either perception (while holding action constant) or action (while holding perception constant). With regard to the spatial updating processes that operate on representation and action, we were interested in whether the type of distance estimation task used in pre- and posttest affects the recalibration effect. We examined these issues by directly comparing the amount of recalibration in blindfolded walking versus imagined walking tasks when the perception-action link was manipulated via differences in rate of visual motion (while keeping walking speed constant) versus differences in walking speed (while keeping rate of visual motion constant). We also examined the role of the organism by looking at recalibration across development. We tested both adults and 12-year-old children in the standard blindfolded walking recalibration task and an imagined walking recalibration task, using the standard manipulation of visual motion (while holding walking speed constant). Finally, we examined whether the type of environment in which participants make their pre- and posttest distance estimates affects the recalibration of perception and action by comparing imagined walking estimates in real and virtual environments. Table A1 shows the eight experimental manipulations.

# CHAPTER 2: EXPERIMENTS 1a, 1b, and 1c

The goal of Experiments 1a, 1b, and 1c was to determine whether children and adults recalibrate perception and action in the standard blindfolded walking task when we manipulate either the rate of visual motion (while keeping walking speed constant) or the walking speed (while keeping the rate of visual motion constant). In Experiment 1a, we had adult participants walk on a treadmill in an immersive virtual environment with the rate of visual motion either twice as fast or half as fast as their walking speed. As in previous work, we expected participants in the fast visual motion condition to undershoot distances at posttest relative to pretest, and participants in the slow visual motion condition to overshoot distances at posttest relative to pretest. In Experiment 1b, we repeated the methods of 1a with 12-year-old children. In Experiment 1c, we had adult participants walk on the treadmill at either a fast or slow walking speed during adaptation while keeping the rate of visual motion the same between conditions. The mismatch of perception and action in Experiment 1c was similar to the mismatch in Experiment 1a and 1b except that it was produced by changing the amount of movement required to travel the same apparent visual distance. If recalibration occurs, participants in the slow walking condition of Experiment 1c should undershoot distance at posttest relative to pretest (since during adaptation it took them less physical movement to cover a given visual distance) and participants in the fast walking condition should overshoot distance at posttest relative to pretest (since during adaptation it took them more physical movement to cover a given visual distance).

# Experiment 1a Method

## Participants

Twenty-three adults (9 females) participated. Participants were recruited from an introductory psychology course at the University of Iowa and received course credit for their participation.

## Apparatus and Materials

The virtual environment was a repeating section of hallway modeled after the actual hallway used in pre- and posttest. The virtual environment was displayed on three 10-feet wide x 8-feet high screens placed at right angles relative to one another, forming a three-walled room. To accommodate the height of the recessed treadmill, the floor on which participants stood was 1 ft. above the bottom of the vertical screens, so the effective screen height was 7 ft. Participants stood on the treadmill approximately 5 ft. from the front screen, midway between the side screens. Three Projection Design F1+ projectors were used to rear project high-resolution graphics (1280 x 1024 pixels) onto the screens, providing participants with approximately (depending on the participant's height) 224 degrees horizontal and 46 degrees vertical FOV of nonstereoscopic, immersive visual imagery. The viewpoint of the scene was adjusted for each participant's eye height.

The treadmill was a Woodway Wide Path motorized treadmill. The belt of the treadmill was 21.5 in. wide and 45 in. long. While walking on the treadmill, participants wore a full-body safety harness (Safewaze Apache), which was attached to the ceiling to prevent them from falling. Participants wore a Mindfold blindfold and headphones playing white noise while making blindfolded walking distance estimates during the preand posttest phases. The target consisted of a green circle (13 in. in diameter, .25 in. thick) placed on the floor with the center of the circle at the target distance for each trial. Participants' distance estimates were measured using a Bosch digital laser finder (model DLR165K).

## Design and Procedure

Distance estimation pretest

Participants were first allowed to practice walking blindfolded to the end of the hallway and back (hallway length was 83 feet). Participants then performed a blindfolded walking distance estimation pretest. This task was completed in a hallway directly outside of the virtual environment lab. For each trial, participants viewed a target on the floor for 5 s and then put on a blindfold and attempted to walk to the target location. Participants were instructed to form a good mental image of the target and the surrounding environment while viewing the target. They were informed that an experimenter would move the target out of the way and that they were to stop when they thought they were in the exact spot the target had been. Once they felt they had formed a good mental image, they pulled down the blindfold and attempted to walk to the target. If participants veered too far to the left or right while walking blindfolded, the experimenter would tap them gently on the arm to correct their path to prevent them from making contact with the hallway wall. The pretest began with two practice trials with targets located at 7 and 9 m. Participants did not wear the white noise headphones during the two practice trials to allow the experimenters to give directions and participants to ask questions. During the test trials, targets were located at 6, 8, and 10 m. Participants saw each distance three times, randomly ordered in blocks of three (9 trials total). After each trial, the experimenter led the participant back to the starting position while still blindfolded. Participants received no feedback about their estimates during practice or test trials.

Adaptation

The adaptation phase began immediately after the pretest. Participants were taken into the lab, outfitted with the safety harness and asked to step onto the treadmill (Figure B1). Before the displays were turned on, participants were allowed to walk on the treadmill for approximately one minute in order to familiarize them with walking on the treadmill and to select a comfortable walking speed. All participants started at 3mph speed and then told the experimenter whether they wanted to walk faster or slower. The experimenter then adjusted the walking speed up or down until the participant felt comfortable. The mean walking speed was 2.89 mph, (*SD* = .198). Participants then walked through an immersive virtual environment on the treadmill for 10 minutes at the walking speed they had selected. The interface was configured such that the rate of visual motion was either half as fast (slow visual motion condition) or twice as fast (fast visual motion condition) as the participant's walking speed. The virtual environment was a model of the same hallway in which the pre- and posttest were conducted (Figure B2). Participants were told to look for ducks and bunnies hidden in the doorways of the hallway while walking through the virtual environment, and to report when they saw one. The search for ducks and bunnies was designed to encourage participants to look from side to side while walking to enhance their perception of lamellar flow (see Durgin, Pelah, Fox, Lewis, & Walley, 2005).

Distance estimation posttest

Immediately following adaptation, participants completed the blindfolded walking distance estimation posttest. Participants were blindfolded then led off of the treadmill and back out to the hallway. Participants then repeated the same blindfolded walking distance estimation task used in the pretest. The target distances were 6, 8, and 10 m presented in 3 blocks, each in a new random order.

Measures

Scores represented the percentage of distance walked at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. This measure allowed us to look at the extent to which subjects overshot or undershot the target relative to their pretest distance estimations. Three participants with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. Two of these excluded participants were in the fast visual motion condition and one was in the slow visual motion condition.

Experiment 1a Results and Discussion

We first examined the extent to which participants undershot or overshot the actual distances prior to any recalibration experience. Participants' mean pretest distance estimation scores were 5.49 m (*SD* = .79) for the 6 m distance, 7.68 m (*SD* = .99) for the 8 m distance, and 10.54 m (*SD* = 1.34) for the 10 m distance. Only the 6 m pretest estimate differed significantly from the actual distance (Figure B6). Thus, participants' mean pretest estimates were quite accurate.

The main goal of Experiment 1a was to replicate the standard recalibration effect (i.e., underestimation of distance following a faster visual motion experience and overestimation of distance following a slower visual motion experience). Percentage scores were entered into a Condition (fast visual motion vs. slow visual motion) x Distance (6 vs. 8 vs. 10 m) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. If recalibration is successful, we would expect that the percentage of distance walked at posttest relative to pretest would be significantly larger in the slow visual motion condition than in the fast visual motion condition. As expected, we found a significant effect of condition, $F$ (1, 18) = 5.25, $p < .05$, with the mean for the fast visual motion group ($M$ = 98.53, $SD$ = 9.13) significantly lower than the mean for the slow visual motion group ($M$ = 106.54, $SD$ = 5.65; Figure B3), indicating that the recalibration experience affected distance estimates at posttest in the expected direction. There was also a significant effect of distance, $F$ (1, 18) = 4.65, $p < .05$, but no significant interaction between condition and distance, $F$ (1, 18) = .19, *ns*. Across both conditions, participants tended to overshoot more at the shorter distances and undershoot more at the longer distances. Mean percentage scores were 105.62% ($SD$ = 12.25) for the 6 m distance, 102.33% ($SD$ = 8.82) for the 8 m distance, and 98.45% ($SD$ = 11.25) for the 10 m distance. Percentage scores for the 6 m and the 10 m distance differed significantly, but did not differ significantly for the 8 m and 10 m distance, or for the 6 m and 8 m distance.

The results of Experiment 1a indicate that participants in our task recalibrated the link between perception and action when the rate of visual motion was manipulated during adaptation and the walking speed was held constant. Although the effect was not large given the amount of increase or decrease in the rate of visual motion, the results of this study are consistent with the effects of previous recalibration studies that manipulated the rate of visual motion to produce recalibration (Mohler et al., 2004, Mohler et al., 2007, Rieser et al., 1995).

The goal of Experiment 1b was to examine whether recalibration occurs to the same degree in younger children as it does in adults. We tested 12-year-old children in the recalibration task.

## Experiment 1b Method

### Participants

Twenty-seven 12-year-old children (15 females) participated. Participants were recruited from a child research participant database maintained by the Department of Psychology at the University of Iowa. Participants received a letter describing the study followed by a telephone call inviting children to participate.

### Apparatus and Materials

The apparatus and materials were identical to those used in Experiment 1a.

### Design and Procedure

#### Distance estimation pretest

Children were first allowed to practice walking blindfolded to the end of the hallway and back (hallway length was 83 feet). The children then performed a blindfolded walking distance estimation pretest identical to the task used in Experiment 1a. This task was completed in a hallway directly outside of the virtual environment lab. For each trial, children viewed a target on the floor for 5 s and then put on a blindfold and attempted to walk to the target location. The pretest began with two practice trials with targets located at 7 and 9 m. During the test trials, targets were located at 6, 8, and 10 m. Children saw each distance three times, randomly ordered in blocks of three (9 trials total). After each trial, the experimenter led the participant back to the starting position while still blindfolded. The children received no feedback about their estimates during practice or test trials.

Adaptation

The adaptation phase began immediately after the pretest and was identical to the adaptation phase used in Experiment 1a. Before the displays were turned on, children were allowed to walk on the treadmill for approximately one minute in order to familiarize them with walking on the treadmill and to select a comfortable walking speed. For Experiment 1b, all child participants started at 2mph speed and then told the experimenter whether they wanted to walk faster or slower. The experimenter then adjusted the walking speed up or down until the participant felt comfortable. The mean walking speed was 2.11 mph, (*SD* = .177). Children then walked through an immersive virtual environment on the treadmill for 10 minutes at the walking speed they had selected. The interface was configured such that the rate of visual motion was either half as fast (slow visual motion condition) or twice as fast (fast visual motion condition) as the participant's walking speed. Children were told to look for ducks and bunnies hidden in the doorways of the hallway while walking through the virtual environment, and to report when they saw one.

Distance estimation posttest

Immediately following adaptation, children completed the blindfolded walking distance estimation posttest identical to Experiment 1a. Children were blindfolded then led off of the treadmill and back out to the hallway. They then repeated the same blindfolded walking distance estimation task used in the pretest. Children saw each distance (6, 8, and 10 m) three times, randomly ordered in blocks of three (9 trials total).

Measures

Scores represented the percentage of distance walked at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. This measure allowed us to look at the extent to which subjects overshot or undershot the target relative to their pretest distance estimations. Two children with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. One of these excluded children was in the fast visual motion condition and one was in the slow visual motion condition.

Experiment 1b Results and Discussion

We first examined the extent to which children undershot or overshot the actual distances prior to any recalibration experience. Children's mean pretest distance estimation scores were 5.17 m (*SD* = .97) for the 6 m distance, 7.57 m (*SD* = 1.62) for the 8 m distance, and 9.86 m (*SD* = 1.92) for the 10 m distance. Only the 6 m pretest estimate differed significantly from the actual distance (Figure B9). Thus, children's mean pretest estimates were reasonably accurate.

The main goal of Experiment 1b was to replicate the standard recalibration effect with 12-year-old children (i.e., underestimation of distance following a faster visual motion experience and overestimation of distance following a slower visual motion experience). Percentage scores were entered into a Condition (fast visual motion vs. slow visual motion) x Distance (6 vs. 8 vs. 10 m) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. If recalibration is successful, we would expect that the percentage of distance walked at posttest relative to pretest would be significantly larger in the slow visual motion condition than in the fast visual motion condition. However, we did not find a significant effect of condition, $F$ (1, 25) = .688, $p$ = .415, *ns*. The mean for the fast visual motion group ($M$ = 100.38, $SD$ = 5.89) did not significantly differ from the mean for the slow visual motion group ($M$ = 103.13, $SD$ = 10.48; Figure B5), indicating that the recalibration experience did not significantly affect distance estimates at posttest. There was a significant effect of distance, $F$ (1, 25) = 10.26, $p$ < .01, but no significant interaction between condition and distance, $F$ (1, 25) = .155, $p$ = .697 *ns*. Across both conditions, participants tended to overshoot more at the shorter distances and undershoot more at the longer distances. Mean percentage scores were 106.79% ($SD$ = 10.65) for the 6 m distance, 100.57% ($SD$ = 11.44) for the 8 m distance, and 98.05% ($SD$ = 11.60) for the 10 m distance. Percentage scores for the 6 m and the 8 m distance and the 6 m and 10 m differed significantly, but did not differ significantly for the 8 m and 10 m distance.

The results of Experiment 1b indicate that 12-year-old children do not exhibit the recalibration effect to the same extent as adults. One reason for this difference may be that the task is not sensitive enough to pick up on changes in perception-action recalibration. That is, children may be recalibrating to the same extent as adults, but the blindfolded walking task may not be the best task for children to demonstrate that recalibration. Another reason might be that children are more variable than adults, thus making the effect harder to observe. Finally, children may not recalibrate as quickly or as easily to changes in perception and action coupling as adults do. Perhaps a longer adaptation period or bigger perception-action mismatch is needed in order to observe recalibration in children. These possibilities are discussed further in the General Discussion.

The goal of Experiment 1c was to examine whether participants also recalibrate perception and action when the walking speed is manipulated during adaptation and the rate of visual motion is held constant. We also videotaped participants' blindfolded walking distance judgments during both pre- and posttest in order to determine if they walked faster or slower at posttest relative to pretest and also to see if, despite how much they may overshoot or undershoot the target during posttest, both groups walked for the same amount of time during posttest after their adaptation experience in the virtual environment.

## Experiment 1c Method

### Participants

Thirty-five adults (18 females) participated. Participants were recruited in the same manner as in Experiment 1a.

### Apparatus and Materials

The virtual environment and treadmill were the same as those used in the previous experiments. For this and the remaining experiments, a Sanyo PLC-WXE45 projector was used to project the ground surface around the treadmill onto the floor. While walking on the treadmill, participants wore a full-body safety harness (Petzl 8003 Full Body harness) attached to the ceiling. The blindfold and target were identical to those used in Experiments 1a and 1b. Participants again wore headphones that played white noise in order to eliminate any ambient sound cues in the environment. Participants' distance estimations were measured using the same Bosch digital laser range finder as was used in Experiments 1a and 1b. We also used a video camera mounted on a tripod to videotape participants' pre- and posttest blindfolded walking.

## Design and Procedure

### Distance estimation pretest

The pretest was identical to the blindfolded walking distance estimation pretest used in Experiments 1a and 1b.

### Adaptation

The adaptation phase began immediately after the pretest. Participants were taken into the lab, outfitted with the safety harness and asked to step onto the treadmill. Participants were assigned to either a fast (3.5 mph) or slow (1.5 mph) treadmill walking speed. The rate of visual motion for both conditions was the same (2.5 mph).[1] Before the displays were turned on, participants were allowed to walk on the treadmill for approximately 30 seconds in order to familiarize them with walking on the treadmill at their assigned walking speed. Participants then walked through the virtual hallway on the treadmill for 10 minutes at either the fast or slow walking speed. Participants were told to look for ducks and bunnies hidden in the doorways of the hallway while walking through the virtual environment, and to report when they saw one.

[1] We were unable to use the same 1:2 rate of visual motion to walking speed as we used in the first set of experiments because we were constrained by how fast we could make participants walk on the treadmill before their gait would change to a run.

Distance estimation posttest

Immediately following adaptation, participants completed the distance estimation posttest. Participants were blindfolded and led off of the treadmill back out to the hallway. Participants then repeated the same blindfolded walking distance estimation task used in the pretest.

## Measures

Scores represented the percentage of the time estimated at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. Five participants with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. Three of the excluded participants were in the fast walking speed condition and two were in the slow walking speed condition.

Video recordings of participants' blindfolded walking during the pretest and posttest were coded for the time elapsed from start to stop. This measure allowed us to determine whether participants walked faster or slower after fast or slow walking adaptation experience in the virtual environment. Inter-coder reliability ($N$ = 5) was $r$ = .967 for time to walk to the target. We used the time and distance participants walked to calculate their walking speed during pre- and posttest distance estimation tests.

## Experiment 1c Results and Discussion

We again first examined participants' pretest distance estimates relative to the actual target distances. Mean estimated pretest distances were 5.05 m (*SD* = .69) for the 6 m distance, 7.30 m (*SD* = 1.0) for the 8 m distance, and 10.01 m (*SD* = 1.54) for the 10 m distance (Figure B7). The 6 m and 8 m pretest estimates differed significantly from the actual distances, but not the 10 m pretest estimates. Again, this shows that participants' pretest distance estimates were reasonably accurate.

The goal of Experiment 1c was examine whether the recalibration effect could be achieved by manipulating action (walking speed) instead of perception (rate of visual motion). Percentage scores were entered into a Condition (2) x Distance (3) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. There was a significant effect of condition, $F$ (1, 28) = 6.63, $p <$ .05, indicating that the mean for the fast visual motion condition ($M$ = 106.6, $SD$ = 6.74) was significantly higher than that for the slow visual motion condition ($M$ = 99.99, $SD$ = 7.32; Figure B3). There was also a significant effect of distance, $F$ (1, 28) = 8.40, $p < .01$, but no significant Distance x Condition interaction, $F$ (1, 28) = .24, *ns*. Participants tended to overshoot more for targets at shorter than at longer distances. Mean percentage scores were 106.10% ($SD$ = 7.1) for the 6 m distance, 102.52% ($SD$ = 10.31) for the 8 m distance, and 101.26% ($SD$ = 9.87) for the 10 m distance. Percentage scores differed significantly between the 6 m and the 8 m distance, and the 6 m and 10 m distance, but not between the 8 m and 10 m distance.

We also analyzed the amount of time it took participants to walk to the target when walking blindfolded at pre- and posttest. Although walking times did not differ significantly between the two conditions, participants who walked faster on the treadmill during adaptation (fast-walking condition) walked significantly faster at posttest relative to pretest compared to participants who walked slower on the treadmill during adaptation (slow-walking condition), $F$ (1, 28) = 8.50, $p < .01$. The mean percentage of walking speed at posttest relative to pretest for participants in the fast walking condition was

114.28% (*SD* = 13.22), while the mean percentage of walking speed at posttest relative to pretest for the slow walking condition was 102.42% (*SD* = 8.57). This suggests that participants adapted to different walking speeds during the recalibration experience. At posttest, participants in both walking speed conditions walked for the same amount of time to reach the targets while blindfolded walking, but participants in the fast walking speed condition walked faster (and therefore went further), whereas participants in the slow walking speed condition walked slower (and therefore went a shorter distance).

Together, Experiments 1a and 1c demonstrate that recalibration occurs with adults regardless of whether we manipulate perception or action. Since both perception and action are crucial parts of recalibration, manipulating either mechanism should result in a change in the perception-action relationship, measurable through changes in the distance walked at posttest relative to pretest.

# CHAPTER 3: EXPERIMENTS 2a, 2b, and 2c

Experiments 1a and 1c clearly show that adult participants exhibited a recalibration effect in their blindfolded walking distance estimates whether we manipulate the rate of visual motion *or* the walking speed during adaptation. However, 12-year-old children did not exhibit a recalibration effect when we manipulated rate of visual motion. One question this raises is whether these effects extend to imagined walking distance estimates. The spatial updating processes that operate on representation of the environment during imagined walking may differ from that during blindfolded walking because there is no proprioceptive feedback about movement through the environment. As a result, we expected to find less robust recalibration results when testing participants via imagined walking.

In Experiment 2a, we manipulated the rate of visual motion during the adaptation phase and used an imagined walking distance estimation task at pre- and posttest. In Experiment 2b, we replicated 2a with 12-year-old children participants in order to see if the imagined walking task yielded different results than blindfolded walking task (Experiment 1b) when looking at recalibration in children. In Experiment 2c, we manipulated the walking speed during the adaptation phase and again used an imagined walking distance estimation task at pre- and posttest.

## Experiment 2a Method

### Participants

Thirty adults (12 females) participated. Participants were recruited in the same manner as previous experiments.

## Apparatus and Materials

The virtual environment and treadmill were the same as was used in Experiment 1a, 1b, and 1c. While walking on the treadmill, participants wore a Safewaze Apache full-body harness attached to the ceiling. Participants wore a Mindfold blindfold and viewed the same target while making imagined walking distance estimates during the pre- and posttest phases. They used a hand-held, digital stopwatch to indicate the time they imagined it would take them to walk to the targets.

## Design and Procedure

### Distance estimation pretest

Participants first performed an imagined walking distance estimation pretest. This task was completed in a hallway directly outside of the virtual environment lab. We first obtained an estimated walking speed (sans blindfold) for participants by having them walk the length of the hallway (83 ft) two times. We took the average of these two trials to compute each participant's estimated walking speed. For each trial during the distance estimation task, participants viewed a target on the floor for 5 s and then pulled down the blindfold and imagined walking to the target location. Participants were instructed to form a good mental representation of the target and the surrounding environment while viewing the target. Participants started the stopwatch when they imagined starting to walk to the target and stopped the stopwatch when they imagined reaching the target. Participants stood in place while making imagined walking distance estimations. As in the previous experiments, the pretest began with two practice trials with targets located at 7 and 9 m and was followed by 9 test trials with targets located at 6, 8, and 10 m. After each trial, the experimenter took the stopwatch from the participant and recorded the time elapsed. Participants were not allowed to see their times and received no feedback about their estimates during practice or test trials.

Adaptation

The adaptation phase began immediately after the pretest and followed the same procedure as in Experiment 1a. The interface of the virtual environment was again configured such that the rate of visual motion was either half as fast (slow visual motion condition) or twice as fast (fast visual motion condition) as the participant's walking speed. The virtual hallway was identical to that used in the previous experiments. Participants were told to look for ducks and bunnies hidden in the doorways of the hallway while walking through the virtual environment, and to report when they saw one.

Distance estimation posttest

Immediately following adaptation, participants completed the imagined walking distance estimation posttest. Participants were blindfolded and then led off of the treadmill and back out to the hallway. Participants then repeated the same imagined walking distance estimation task used in the pretest.

## Measures

Scores represented the percentage of the time estimated at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. Three participants with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. One excluded participant was in the fast visual motion condition and the other two were in the slow visual motion condition.

## Experiment 2a Results and Discussion

We first examined participants' pretest distance estimation scores relative to the actual distance of the target. For these analyses, we used participants' baseline walking speed to convert their imagined walking times into distances. Mean estimated pretest distances for participants were 5.93 m ($SD$ = 1.67) for the 6 m distance, 8.46 m ($SD$ = 2.70) for the 8 m distance, and 11.13 m ($SD$ = 3.64) for the 10 m distance. None of these distance estimations differed significantly from the actual target distance (Figure B8). Thus, participants' pretest estimates were quite accurate, even when estimating the time required to reach the target.

The goal of Experiment 2a was again to replicate the standard recalibration procedure, this time with an imagined walking distance estimation task at pre- and posttest, to examine whether participants flexibly recalibrate perception and action. Percentage scores were entered into a Condition (2) x Distance (3) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. Analyses showed a significant effect of condition, $F$ (1, 25) = 8.54, $p$ < .01. The mean percentage score in the fast visual motion condition ($M$ = 88.24, $SD$ = 11.41) was significantly smaller than the mean percentage score in the slow visual motion condition ($M$ = 101.51, $SD$ = 12.19; Figure B4). There was no significant main effect of distance, $F$ (1, 25) = 3.76, $p$ = .06, and no Distance x Condition interaction. $F$ (1, 25) = .01, *ns*.

The results of Experiment 2a indicate that when the rate of visual motion was manipulated during adaptation, people exhibited a recalibration effect during imagined walking similar to that observed during blindfolded walking. The goal of Experiment 2b was to examine whether 12-year-old children show a recalibration effect when the distance estimation task is imagined walking rather than blindfolded walking.

## Experiment 2b Method

### Participants

Twenty-nine 12-year-old children (14 females) participated. Participants were recruited in the same manner as Experiment 1b.

### Apparatus and Materials

The virtual environment and treadmill were the same as was used in the previous experiments. While walking on the treadmill, participants wore a Safewaze Apache full-body harness attached to the ceiling. Children wore a Mindfold blindfold and viewed the same target while making imagined walking distance estimates during the pre- and posttest phases. They used a hand-held, digital stopwatch to indicate the time they imagined it would take them to walk to the targets.

### Design and Procedure

#### Distance estimation pretest

Children first performed an imagined walking distance estimation pretest identical to that used in Experiment 2a. This task was completed in a hallway directly outside of the virtual environment lab. For each trial during the distance estimation task, children viewed a target on the floor for 5 s and then pulled down the blindfold and imagined walking to the target location. Children started the stopwatch when they imagined starting to walk to the target and stopped the stopwatch when they imagined reaching the target. As in the previous experiments, the pretest began with two practice trials with targets located at 7 and 9 m and was followed by 9 test trials with targets located at 6, 8, and 10 m. After each trial, the experimenter took the stopwatch from the child and recorded the time elapsed. Children were not allowed to see their times and received no feedback about their estimates during practice or test trials.

Adaptation

The adaptation phase began immediately after the pretest and followed the same procedure as in Experiment 1a, 1b, and 2a. Before the displays were turned on, children were allowed to walk on the treadmill for approximately one minute in order to familiarize them with walking on the treadmill and to select a comfortable walking speed. For Experiment 2b, all child participants started at 2mph speed and then told the experimenter whether they wanted to walk faster or slower. The experimenter then adjusted the walking speed up or down until the child felt comfortable. The mean walking speed was 1.92 mph, (*SD* = .188). Children then walked through an immersive virtual environment on the treadmill for 10 minutes at the walking speed they had selected. The interface of the virtual environment was again configured such that the rate of visual motion was either half as fast (slow visual motion condition) or twice as fast (fast visual motion condition) as the child's walking speed. The virtual hallway was identical to that used in the previous experiments. Children were told to look for ducks and bunnies hidden in the doorways of the hallway while walking through the virtual environment, and to report when they saw one.

Distance estimation posttest

Immediately following adaptation, children completed the imagined walking distance estimation posttest identical to that used in Experiment 2a. Children were blindfolded and then led off of the treadmill and back out to the hallway. They then repeated the same imagined walking distance estimation task used in the pretest.

## Measures

Scores represented the percentage of the time estimated at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. Three children with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. One excluded child was in the fast visual motion condition and the other two were in the slow visual motion condition.

## Experiment 2b Results and Discussion

We first examined children's pretest distance estimation scores relative to the actual distance of the target. For these analyses, we used children's baseline walking speed to convert their imagined walking times into distances. Mean estimated pretest distances for child participants were 4.69 m (*SD* = 1.09) for the 6 m distance, 6.71 m (*SD* = 2.0) for the 8 m distance, and 7.98 m (*SD* = 2.55) for the 10 m distance. All three of these distance estimations differed significantly from the actual target distance (Figure B9). Thus, 12-year-olds' imagined walking estimates at pretest were clearly short of the distance required to reach the target.

The goal of Experiment 2b was again to replicate the standard recalibration procedure with 12-year-old children, this time with an imagined walking distance estimation task at pre- and posttest, to examine whether child participants flexibly recalibrate perception and action. Percentage scores were entered into a Condition (2) x Distance (3) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. Analyses showed no significant effect of condition, $F$ (1, 26) = .847, $p$ = .366, *ns*. The mean percentage score in the fast visual motion condition ($M$ = 89.37, $SD$ = 16.42) did not differ significantly from the mean percentage score in the slow visual motion condition ($M$ = 94.51, $SD$ = 13.42; Figure B5). There was no significant main effect of distance, $F$ (1, 27) = 1.21, $p$ = .299, and no Distance x Condition interaction. $F$ (1, 27) = .721, *ns*.

The results of Experiment 2b indicate that when the rate of visual motion was manipulated during adaptation, 12-year-old children still did not exhibit a measureable recalibration effect even when the imagined walking task was used in pre- and posttest. Although we observed an even stronger effect of recalibration in adults when the imagined walking task was used, 12-year-old children did not show a significant effect of recalibration with these methods. Possible reasons for this difference are discussed in the General Discussion.

The goal of Experiment 2c was to examine whether adult participants also recalibrate perception and action during imagined walking when the walking speed is manipulated during adaptation while rate of visual motion is held constant.

## Experiment 2c Method

### Participants

Thirty-four participants (18 females) participated. Participants were recruited in the same manner as Experiments 1a, 1c, and 2a.

### Apparatus and Materials

The apparatus and materials were identical to those used in Experiments 2a and 2b. Participants wore a Petzl 8003 Full Body Harness while walking on the treadmill.

## Design and Procedure

### Distance estimation pretest

The imagined walking distance estimation task at pretest was identical to that used in Experiments 2a and 2b.

### Adaptation

The adaptation phase began immediately after the pretest and was identical to the adaptation phase of Experiment 1c. Participants walked through the virtual hallway on the treadmill for 10 minutes at either the fast (3.5 mph) or slow walking speed (1.5 mph). The rate of visual motion for both conditions was the same (2.5 mph).

### Distance estimation posttest

Immediately following adaptation, participants completed the same imagined walking distance estimation task used in the pretest. Participants were blindfolded and led off of the treadmill and back out to the hallway.

## Measures

Scores represented the percentage of distance walked at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. Four participants with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. Two excluded participants were in the fast walking speed condition and two were in the slow walking speed condition.

## Experiment 2c Results and Discussion

We first examined participants' pretest distance estimation scores relative to the actual target distances. Participants' baseline walking speed was used to convert their imagined walking timed estimates into distances. Mean estimated pretest distances for participants were 5.27 m (*SD* = 1.66) for the 6 m distance, 7.59 m (*SD* = 2.45) for the 8 m distance, and 10.00 m (*SD* = 3.26) for the 10 m distance. Only the 6 m pretest estimate differed significantly from the actual distance (see Figure B8).

The goal of Experiment 2c was to test perception-action recalibration using an imagined walking task when action (walking speed) was altered during adaptation rather than perception (rate of visual motion). Percentage scores were entered into a Condition (2) x Distance (3) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. Although Experiment 2a revealed a strong effect of condition when the rate of visual motion was manipulated during adaptation, we found no significant difference between the fast-walking ($M$ = 95.97, $SD$ = 3.24) and slow-walking groups ($M$ = 98.3, $SD$ = 3.6) , $F$ (1, 28) = .23, *ns* (Figure B4). There was no effect of distance, $F$ (1, 28) = .02, *ns,* and no Distance x Condition interaction, $F$ (1, 28) = .15, *ns*.

Although we observed perception-action recalibration when we manipulated rate of visual motion during adaptation and used the imagined walking task at test, we did not see the recalibration effect when we manipulated the walking speed during adaptation. Possible reasons for this are presented in the General Discussion.

# CHAPTER 4: EXPERIMENT 3a and 3b

Experiment 3a and 3b explored how the testing environment affects the recalibration of action and perception. Of particular interest was whether perception-action coupling is more malleable when tested in a virtual environment. Participants in this study completed both the pre- and posttest imagined walking distance estimation task in the same virtual hallway environment as was used during the adaptation phase. We manipulated rate of visual motion in Experiment 3a and walking speed in Experiment 3b.

## Experiment 3a Method

### Participants

Thirty-one adults (18 females) participated. Participants were recruited in the same manner as in the previous experiments.

### Apparatus and Materials

We used the same virtual environment and treadmill as in the previous experiments. During the entire experiment, participants wore a Safewaze Apache full-body safety harness that was attached to the ceiling. Participants wore a Mindfold blindfold while making imagined walking distance estimates and stood on a platform that sat over the treadmill during the pre- and posttest phases. They used a hand-held, digital stopwatch to indicate the time they imagined it would take them to walk to the target in a given trial. The target consisted of a virtual green circle (13 in. in diameter, .25 in. thick) that appeared on the floor of the virtual hallway, with the center of the circle at the target distance for each trial.

## Design and Procedure

Distance estimation pretest

The pretest used in Experiment 3a was identical to the imagined walking distance estimation pretest used in the previous experiments, except that participants made distance estimations in the virtual hallway instead of the real hallway. After outfitting participants with the safety harness, we first obtained an average walking speed (sans blindfold) for participants by having them walk two lengths of the hallway on the treadmill in the virtual environment. Participants were able to adjust their walking speed to a comfortable rate on the treadmill. The average walking speed on the treadmill for participants in Experiment 3a was 2.91 m/s ($SD$ = .184). During pretest and posttest, participants stood on a 1.5-in. high platform that sat over the treadmill belt so that they would not be standing blindfolded on a treadmill. (When stopped, the treadmill belt tended to move slightly sometimes which was problematic when participants were standing blindfolded on the treadmill.) For each trial during the distance estimation task, participants viewed a target on the floor of the virtual hallway for 5 s and then put on a blindfold and imagined walking to the target location. As in previous experiments, participants completed the two practice trials and nine test trials without feedback.

Adaptation

The adaptation phase began immediately after the pretest. The experimenter removed the platform so that participants could walk on the treadmill. The adaptation experience was identical to that used in the previous experiments. Participants walked through the virtual hallway on the treadmill for 10 minutes with the rate of visual motion either twice as fast (fast condition) or half as fast (slow condition) as the participant's walking speed. Participants were told to look for ducks and bunnies hidden in the doorways of the hallway while walking through the virtual environment, and to report when they saw one.

Distance estimation posttest

Immediately following adaptation, participants completed the distance estimation posttest. The experimenter replaced the platform over the treadmill, and participants stood on the platform while making distance estimations in the virtual environment. Participants repeated the same imagined walking distance estimation task used in the pretest with target distances at 6, 8, and 10m.

## Measures

Scores represented the percentage of the time estimated at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10 m) to create a percentage score for each distance. Five participants with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. Three excluded participants were in the fast visual motion condition and two were in the slow visual motion condition.

## Experiment 3a Results and Discussion

We first examined participants' pretest distance estimates relative to the actual target distances. We used participants' treadmill walking speed to convert their estimated times into distances. Mean estimated pretest distances were 3.66 m (*SD* = 1.16) for the 6 m distance, 5.62 m (*SD* = 1.55) for the 8 m distance, and 7.43 m (*SD* = 2.14) for the 10 m distance. All three pretest target distance estimations differed significantly from the actual target distances (Figure B10). As in other studies, participants underestimated distances significantly in the virtual environment (Grechkin et al., 2011; Swan et al., 2007; Thompson et al., 2004; Witmer & Kline, 1998; Witmer & Sadowski, 1998).

The goal of Experiment 3a was to see if the environment in which participants completed the imagined walking distance estimates affected their recalibration of perception and action. Percentage scores were entered into a Condition (2) x Distance (3) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. There was a highly significant main effect of condition, $F$ (1, 24) = 35.21, $p < .0001$. Percentage scores in the fast visual motion condition ($M$ = 77.92, $SD$ = 11.13) were significantly smaller than percentage scores in the slow visual motion condition ($M$ = 128.99, $SD$ = 29.97; Figure B6). The underestimation of distance at posttest relative to pretest in the fast visual motion condition is particularly remarkable, considering that the pretest estimates were very low to begin with. There was also a significant effect of distance, $F$ (1, 24) = 9.07, $p < .01$, but no significant Distance x Condition interaction, $F$ (1, 24) = .54, *ns*. Across both conditions, participants tended to overshoot more at the shorter distances and undershoot more at the longer distances. Mean percentage scores were 108.67 % ($SD$ = 40.35) for the 6 m distance, 96.88 % ($SD$ = 30.70) for the 8 m distance, and 98.92 % ($SD$ = 33.44) for the 10 m distance. There was a significant difference between 6 m and 8 m distance estimations, and between the 6 m and 10 m distance estimations, but not between the 8 m and 10 m distance estimations.

Altering the rate of visual motion while keeping the walking speed constant during the adaptation phase resulted in a larger recalibration effect when participants completed the pre- and posttest distance estimations in the virtual environment compared to when they completed pre- and posttest in the real environment. In Experiment 3b, we tested whether altering the walking speed while holding rate of visual motion constant during adaptation also leads to a strong recalibration effect when participants complete the pre- and posttest in the virtual environment. Although we did not see an effect of recalibration when testing distance estimation via an imagined walking task in the real world (Experiment 2c), we suspected that the less-grounded experience of judging distances in the virtual environment might result in a stronger recalibration effect.

## Experiment 3b Method

### Participants

Thirty-four adults (15 females) participated in Experiment 3b. Participants were recruited in the same manner as previous experiments.

### Apparatus and Materials

All apparatus and materials were the same as those used in Experiment 3a. Participants wore a Petzl 8003 Full-Body Harness for the duration of the experiment.

### Design and Procedure

#### Distance estimation pretest

The pretest was identical to the imagined walking pretest used in the previous experiments. Before pretest trials began, participants walked two lengths of the virtual hallway with normal 1:1 ratio of speed of visual flow to walking speed. This was done to give participants some experience with the virtual environment before they were asked to make imagined walking distance estimations. Participants then completed the two practice trials and nine pretest trials while standing on a platform placed over the treadmill.

Adaptation

The adaptation phase began immediately after the pretest and followed the same procedure as Experiments 1c and 2c. Participants were assigned to either a fast-walking (3.5 mph) or a slow-walking (1.5 mph) condition. The rate of visual motion for both conditions was the same (2.5 mph). Before the displays were turned on, participants were allowed to walk on the treadmill for approximately 30 seconds at their assigned walking speed in order to familiarize them with the speed at which they would be moving through the environment during adaptation. Participants then walked through the immersive virtual environment on the treadmill for 10 minutes and reported when they saw ducks and bunnies.

Distance estimation posttest

Immediately following adaptation, participants completed the imagined walking distance estimation posttest. Participants were blindfolded and the experimenter replaced the platform over the treadmill for participants to stand on. Participants then repeated the same imagined walking distance estimation task used in the pretest.

## Measures

Scores represented the percentage of the time estimated at posttest relative to pretest. Posttest means for each distance were divided by pretest means for each distance (6, 8, and 10m) to create a percentage score for each distance. Seven participants with a score 1.5 standard deviations above or below the mean (averaged across distances) were excluded from the analyses. Four excluded participants were in the fast walking speed condition and three were in the slow walking speed condition.

Experiment 3b Results and Discussion

We did not analyze pretest scores in Experiment 3b since participants all walked at a predetermined rate on the treadmill and we were unable to use a baseline walking speed to convert imagined walking times into distances.

Experiment 3a revealed a large recalibration effect when we varied the rate of visual motion between conditions and tested distance estimation in the virtual environment. The goal of Experiment 3b was to determine whether people also exhibited recalibration in an imagined walking task when *action* rather than perception was altered between the two conditions during adaptation. Percentage scores were entered into a Condition (2) x Distance (3) mixed model ANOVA with the first factor as a between-subjects variable and the second factor as a within-subjects variable. Surprisingly, we found no significant difference between the fast- and slow-walking groups, (fast-walking $M$ = 103.3, $SD$ = 11.36; slow-walking $M$ = 100.47; $SD$ = 12.25) F (1, 25) = .38, *ns* (Figure B6). There was a significant effect of distance, $F$ (1, 25) = 5.32, $p < .05$, but no significant Distance x Condition interaction, $F$ (1, 25) = .31, *ns*. Across conditions, participants tended to overshoot target distances that were shorter and undershoot target distances that were longer. Mean percentage scores were 109.92% ($SD$ = 24.48) for the 6 m distance, 97.21% ($SD$ = 11.74) for the 8 m distance, and 98.37% ($SD$ = 12.98) for the 10 m distance. Percentage scores differed significantly between the 6 m distance and the 8 m distance, and the 6 m and 10 m distance, but not between the 8 m and 10 m distance. Thus, when we manipulated walking speed, participants did not exhibit a significant recalibration effect in the imagined walking task even when the pre- and posttest occurred in a virtual environment.

Recalibration scores in Experiments 2a and 3a can be directly compared to those in Experiments 2c and 3b to examine the effect of the environment (real or virtual) in which distance estimates take place. All four of these experiments used imagined walking to test for recalibration; however, in Experiments 2a and 2c participants were tested in the real environment and in Experiments 3a and 3b participants were tested in the same virtual environment that they experienced during adaptation. When comparing Experiments 2a and 3a, we find that the effect of the rate of visual motion manipulation was even stronger when tested in the virtual environment (3a) compared to the real environment (2a). The mean percentage of the distance estimated at posttest relative to pretest in the fast visual motion condition of Experiment 3a (77.92%) was significantly lower than the mean percentage of the distance estimated in the fast visual motion condition of Experiment 2a (88.24%), $F$ (26) = 5.86, $p < .05$. The mean percentage of the distance estimated at posttest relative to pretest in the slow visual motion condition of Experiment 3a (128.99%) was significantly higher than the mean percentage of the distance estimated in the slow visual motion condition of Experiment 2a (101.51%), $F$ (23) = 9.30, $p$ <.01). However, when comparing Experiments 2c and 3b we find that when we manipulated the walking speed during adaptation the recalibration effect did not appear in either the real environment (2c) or the virtual environment (3b). The mean percentage of the distance estimated at posttest relative to pretest in the fast visual motion condition was 95.97% in Experiment 2b and 103.29% in Experiment 3b, $F$ (26) = 2.582, *ns*. The mean percentage of the distance estimated at posttest relative to pretest in the slow visual motion condition was 98.3% in Experiment 2c and 100.47% in Experiment 3b, $F$ (27) = .197, *ns*

When comparing the results of Experiments 2 and 3 we can clearly see that when the rate of visual motion was manipulated, participants showed a much greater recalibration effect when tested in the less-grounded virtual environment as opposed to the real environment. However, when the walking speed was manipulated, we did not observe a recalibration effect in either the real environment or the virtual environment, likely due to the interaction of the type of recalibration manipulation and the distance estimation task.

# CHAPTER 5: GENERAL DISCUSSION

The goal of this investigation was to examine how manipulating perception or action during adaptation influences perception-action recalibration in blindfolded walking and imagined walking tasks. We were also interested in the effect of the testing environment on the recalibration effect, and whether 12-year-old children exhibit perception-action recalibration. Table A2 summarizes the results of all eight experiments. In Experiments 1a and 1c we observed a recalibration effect in the blindfolded walking task when we manipulated either the rate of visual motion (perception) or the walking speed (action). In Experiments 2a and 2c we observed a recalibration effect in the imagined walking task when we manipulated the rate of visual motion during adaptation but not when we manipulated the walking speed. Likewise, in Experiments 3a and 3b we found that when participants performed the imagined walking task in a virtual environment, they showed a strong recalibration effect when we manipulated the rate of visual motion, but no recalibration effect when we manipulated the walking speed. In Experiments 2b and 3b, which examined recalibration in 12-year-old children, we did not see a significant effect of recalibration when the rate of visual motion was manipulated regardless of the distance estimation task used in pre- and posttest.

The results of these experiments underscore the importance of considering how spatial updating processes operate on perception and action during the adaptation phase and on representation and action during the test phase of recalibration experiments. During adaptation, participants walk with their eyes open and learn an altered link between perception and action. During test, participants make distance estimations with their eyes closed and must rely on the link between *representation* and action. When a new pairing of perception and action is learned during adaptation, people presumably recalibrate the perception-action relationship and extend that to the representation-action relationship in order to make distance estimates at test. It is important to note that in all of these experiments, participants experienced a mis-match between perception and action during adaptation – they either experienced faster or slower visual motion while walking speed was held constant or they experienced faster or slower walking speed while rate of visual motion was held constant. At test, all participants made estimates about the same target distances. The only thing that differed was how (blindfolded walking or imagined walking) and in what type of environment (real or virtual) they made their distance estimates. Below, we consider how these manipulations during adaptation and test influenced the recalibration effect.

Previous studies have only examined perception-action recalibration by manipulating the rate of visual motion while holding the walking speed constant during adaptation (e.g. Mohler et al., 2004; Mohler et al., 2007; Rieser et al., 1995). Here, we demonstrate that people exhibit recalibration in the blindfolded walking task regardless of whether perception or action is manipulated during adaptation. Specifically, we found significant recalibration when manipulating either rate of visual motion (while holding the walking speed constant) or walking speed (while holding rate of visual motion constant) during adaptation. This work unequivocally demonstrates that the ratio of walking speed to visual motion is the critical variable in perception-action recalibration. Through experience interacting with the world, people learn to expect a certain visual gain relative to movement produced. If this link is altered by manipulating either perception or action, people adapt relatively quickly to this change as seen when walking blindfolded to targets.

This work also revealed interesting interactions between the type of perception-action manipulation during adaptation and the task used to measure distance estimates at test. In Experiments 2a and 2c we used the imagined walking task to look at the same change in the perception-action link as we did in Experiments 1a and 1c. Unlike the blindfolded walking task, we observed recalibration at test when rate of visual motion was manipulated during adaptation, but not when the walking speed was manipulated during adaptation. The fact that we only observed significant recalibration when the rate of visual motion was manipulated using an imagined walking task demonstrates the importance of the distance estimation task used to measure recalibration.

An important question these findings raise is why do people exhibit perception-action recalibration in imagined walking tasks when the rate of visual motion is manipulated during adaptation but not when the walking speed is manipulated during adaptation? As noted earlier, participants in both sets of experiments had exactly the same experiences during adaptation. Therefore, the fact that we see recalibration with the blindfolded walking task in both the visual motion and walking speed conditions indicates that participants are in fact recalibrating perception and action during the adaptation phase. This means that something about the imagined walking task is different from the blindfolded walking task.

One possible reason why we do not see the recalibration effect in the imagined walking task when manipulating the walking speed during adaptation is that participants are actually imagining themselves walking at a faster or slower rate during test. Note that we do see differences in walking speed at test when using a blindfolded walking task. Specifically, participants tended to walk significantly faster or slower during posttest in Experiment 1b, while still walking for the same amount of time. It is possible that participants in the fast walking condition of Experiment 2c imagined themselves walking faster and participants in the slow walking condition imagined themselves walking slower to cover the same amount of distance. If this was the case, participants should have produced very similar time estimates even though they were imagining themselves walking at different rates. However, the imagined walking task has no way of measuring this. In the future, we may be able to further explore this issue by using a continuous pointing method developed by Siegle, Campos, Mohler, Loomis, and Bulthoff, (2009). In this method, participants attempt to point continuously at a target off to the side as they imagine themselves moving past it. Methods such as these could help us measure how fast participants are imagining themselves walking during pre- and posttest distance estimation and may reveal a difference in walking speed between conditions.

These results also raise the issue of the role of time in the recalibration of perception and action. People may rely on a sense of the amount of time it should take to travel a given distance in order to complete these distance estimation tasks. Typically, researchers emphasize the relationship between speed and distance in recalibrating perception and action. However, it is impossible to separate time out of any equation involving speed and distance since normally the amount of time it takes someone to travel a given distance will systematically change along with any change of speed. Therefore, it is important to consider time as a factor in recalibration studies and to consider the role it may play in combination with the distance estimation task used to measure recalibration.

Experiments 3a and 3b examined the role of the test environment on recalibration. We found that when we manipulated the rate of visual motion and tested participants in the virtual environment, participants showed a much stronger recalibration effect than they did when tested in the real environment. Again, participants showed no recalibration effect in the virtual environment when we manipulated walking speed and tested via imagined walking. The fact that participants undershot the distances even *more* at posttest than pretest when rate of visual motion was manipulated is surprising given how much participants underestimated during pretest in the virtual environment. Based on previous literature, we know that people are less grounded in virtual environments compared to the real environment and tend to underestimate distances until they have been given more experience in the VE (Richardson & Waller, 2007). Being less grounded may have led participants to rely more heavily on the rate of visual motion information learned during adaptation when completing the imagined walking task in the virtual environment during posttest. In sum, people may rely more heavily on a newly learned perception-action link when the environment is unfamiliar or cue-impoverished and they are less grounded in real-world experience.

One final question is why we did not see a recalibration effect when testing 12-year-old children in the recalibration task. There are a few possible reasons why we were unable to observe recalibration with children. One possibility is that children are simply more variable than adults in their distance estimates. In fact when comparing standard deviation scores of child and adult participants (based on their 9 percentage scores), we see that children ($M = 17.44$, $SD = 6.05$) had marginally more variable scores than adults ($M = 13.77$, $SD = 6.24$) when tested with the blindfolded walking task, $F(1, 37) = 3.474$, $p = .07$; and children ($M = 20.94$, $SD = 7.57$) were significantly more variable than adults ($M = 17.06$, $SD = 4.62$) when tested with the imagined walking task, $F(1, 54) = 5.262$, $p < .05$. More variability in the scores indicates that children were less consistent in these tasks, which may have masked any recalibration that they experienced. The imagined walking task in particular may have been confusing for some of the child participants, leading some children to understand and perform the task better than others. So although children may still have recalibrated to these changes in the relationship between perception and action, the variability in pre- and posttest scores may not allow us to observe the differences between conditions.

Another reason for this age difference may be that the tasks used to measure recalibration were not sensitive enough to pick up on subtle changes that children may have been exhibiting. It is important to note how subtle the recalibration effects were even in our adult subjects. Despite changing the relationship between walking speed and rate of visual flow quite drastically during adaptation, the effect of recalibration we observed in our adult subjects was generally much smaller than the amount of perception-action manipulation. Both the blindfolded walking and the imagined walking tasks may not have been sensitive enough to pick up on 12-year-old children's recalibration of perception and action. With a little more variability in the children's scores as compared to adults, these subtle differences between pre- and posttest may have been covered up. Perhaps a different task may have yielded significant recalibration results with child participants.

One final explanation for why 12-year-old children did not demonstrate the recalibration effect with either blindfolded or imagined walking may be that children are less flexible than adults at picking up on small changes to the perception-action system and integrating them into their future action plans. As mentioned in the introduction, children have had less overall experience with their bodies and the normal relationship between perception and action.

Perhaps more adaptation time or a greater change in the perception-action relationship is needed in order for children to pick up on these changes and exhibit significant changes in distance estimates at posttest. Giving children more practice with the distance estimation task is another possible option that may reduce variability in children's scores allowing the recalibration effect to emerge. Finally, since we saw such a large effect of recalibration with adults when tested in the virtual hallway instead of the real hallway after manipulating rate of visual motion, it would be worthwhile to look at how children respond when tested in the same virtual environment that they experience during adaptation. Testing children in a more sensitive task, or allowing them more time and experience in either the distance estimation task, virtual environment, or both, may result in significant recalibration effects in children similar to those found with adults.

Together, these experiments shed light on the underlying spatial updating processes used in recalibration tasks. All participants in these eight experiments experienced a similar adaptation phase involving a mismatch between the walking speed and rate of visual motion. Based on the results with blindfolded walking, we assume that participants recalibrated their perception-action relationship equally during the adaptation phase. However, when participants had to rely on a representation-action relationship during test, the nature of the perception-action manipulation interacted with the type of distance estimation task to determine if the recalibration effect appeared. In sum, although the link between both perception and action and representation and action is subject to recalibration, the type of environment, age of the organism, and distance estimation task clearly influence whether we observe recalibration when people rely on the link between representation and action.

# REFERENCES


Adolph, K. E., & Avolio, A. M. (2000). Walking infants adapt locomotion to changing body dimensions. Journal of Experimental Psychology, 26, 1148-1166.

Banks, M. S. (1988). Visual recalibration and the development of contrast and optical flow perception. In A. Yonas (Ed.), Perceptual Development in Infancy, The Minnesota Symposia on Child Psychology, Vol. 20. (pp. 145-196). Hillsdale, NJ: Lawrence Erlbaum Associates.

Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. Behavioural Brain Research, 31, 1-5.

Durgin, F. H., Pelah, A., Fox, L. F., Lewis, J., Kane, R., & Walley, K. A. (2005). Self-motion perception during locomotor recalibration: More than meets the eye. Journal of Experimental Psychology: Human Perception and Performance, 31, 398-419.

Farrell, M. J., & Thomson, J. A. (1998). Automatic spatial updating during locomotion without vision. The Quarterly Journal of Experimental Psychology, 51A, 637-654.

Farrell, M. J., & Thomson, J. A. (1999). On-line updating of spatial information during locomotion without vision. Journal of Motor Behavior, 31, 39-53.

Garciaguirre, J. S., Adolph, K. E., & Shrout, P. E. (2007). Baby carriage: Infants walking with loads. Child Development, 78, 664-680.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. Annual Review of Psychology, 39, 1-41.

Gibson, J. J. (1979). The ecological approach to visual perception. Hillsdale, NJ: Lawrence Erlbaum Associates.

Grechkin, T. Y., Nguyen, T. D., Plumert, J. M., Cremer, J. F., & Kearney, J. K. (2010). How does presentation method and measurement protocol affect distance estimation in real and virtual environments? ACM Transactions on Applied Perception, 7, 1-18.

Higgins, C. I., Campos, J. J., & Kermoian, R. (1996). Effect of self-produced locomotion on infant postural compensation to optic flow. Developmental Psychology, 32, 836-841.

Interrante, V., Ries, B., & Anderson, L. (2006). Distance perception in immersive virtual environments, revisited. Proceedings of the IEEE Conference on Virtual Reality, 3-10.

Kunz, B. R., Creem-Regehr, S. H., & Thompson, W. B. (2009). Evidence for motor simulation in imagined walking. Journal of Experimental Psychology: Human Perception and Performance, 35, 1458-1471.

Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. Journal of Experimental Psychology, 18, 906-921.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S. H., Willemsen, P., Pick, H. L., Jr., & Rieser, J. J. (2007). Calibration of locomotion resulting from visual motion in a treadmill-based virtual environment. ACM Transactions on Applied Perception, 4, 1-15.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S., Pick, H. L. Jr, Warren, W. Jr., Rieser, J. J., & Willemsen, P. (2004). Visual motion influences locomotion in a treadmill virtual environment. Association for Computing Machinery, Inc., 19-22.

Nguyen, T. D., Ziemer, C. J., Grechkin, T., Chihak, B., Plumert, J. M., Cremer, J. F., & Kearney, J. K. (2011). Effects of scale change on distance perception in virtual environments. ACM Transactions on Applied Perception, 8, 1-18.

Plumert, J. M., Kearney, J. K., Cremer, J. F., & Recker, K. M. (2005). Distance perception in real and virtual environments. ACM Transactions on Applied Perception, 2, 216-233.

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving distance. Psychological Science, 14, 106-112.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. Journal of Experimental Psychology: Learning, Memory, and Cognition, 15, 1157-1165.

Rieser, J. J., Ashmead, D. H., Talor, C. R., & Youngquist, G. A. (1990). Visual perception and the guidance of locomotion without vision to previously seen targets. Perception, 19, 675-689.

Rieser, J. J., Guth, D. A., & Hill, E. W. (1986). Sensitivity to perspective structure while walking without vision. Perception, 15, 173-188.

Rieser, J. J., & Pick, H. J. Jr. (2007). Using locomotion to update spatial orientation: What changes with learning and development? In J. M. Plumert & J. P. Spencer (Eds.) The emerging spatial mind (pp.77-103). New York: Oxford University Press.

Rieser, J. J., Pick, H. J. Jr., Ashmead, D. H., & Garing, A. E. (1995). Calibration of human locomotion and models of perceptual-motor organization. Journal of Experimental Psychology, 21, 480-497.

Richardson, A. R., & Waller, D. (2007). Interaction with an immersive virtual environment corrects users' distance estimates. Human Factors: The Journal of Human Factors and Ergonomics Society, 49, 507-517.

Siegle, J. H., Campos, J. L., Mohler, B. J., Loomis, J. M., & Bulthoff, H. H. (2009). Measurement of instantaneous perceived self-motion using continuous pointing. Experimental Brain Research, 195, 429-444.

Swan, J. E. II., Jones, A., Kolstad, E., Livingston, M. A., & Smallman, H. S. (2007). Egocentric depth judgments in optical, see-through augmented reality. IEEE Transactions on Visualization and Computer Graphics, 13, 429-442.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? Journal of Experimental Psychology: Human Perception and Performance, 9, 427-443.

Thompson, W. B., Willemsen, P., Gooch, A. A., Creem-Regehr, S. H., Loomis, J. M., & Beall, A. C. (2004). Does the quality of the computer graphics matter when judging distances in visually immersive environments? Presence: Teleoperators and Virtual Environments, 13, 560-571.

Waller, D., & Richardson, A. R. (2008). Correcting distance estimates by interacting with immersive virtual environments: Effects of task and available sensory information. Journal of Experimental Psychology: Applied, 14, 61-72.

Withagen, R., & Michaels, C. F. (2002). The calibration of walking transfers to crawling: Are action systems calibrated? Ecological Psychology, 14, 223-234.

Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. Presence, 7, 144-167.

Witmer, B. G., & Sadowski, W. J. (1998). Nonvisually guided locomotion to a previously viewed target in real and virtual environments. Human Factors, 40, 478-488.

Ziemer, C. J., Plumert, J. M., Cremer, J. F., & Kearney, J. K. (2009). Estimating distance in real and virtual environments: Does order make a difference? Attention, Perception, & Psychophysics, 71, 1095-1106.

# APPENDIX A: TABLES

| Experiment | Participants | Task | Manipulation | Environment |
|---|---|---|---|---|
| 1a | Adults | Blindfolded walking | Rate of visual motion | Real hallway |
| 1b | 12-year-old children | Blindfolded walking | Rate of visual motion | Real hallway |
| 1c | Adults | Blindfolded walking | Walking speed | Real hallway |
| 2a | Adults | Imagined walking | Rate of visual motion | Real hallway |
| 2b | 12-year-old children | Imagined walking | Rate of visual motion | Real hallway |
| 2c | Adults | Imagined walking | Walking speed | Real hallway |
| 3a | Adults | Imagined walking | Rate of visual motion | Virtual hallway |
| 3b | adults | Imagined walking | Walking speed | Virtual hallway |

Table A1. The eight experimental manipulations carried out in the present investigation.

| Experiment | Participants | Task | Manipulation | Environment | Recalibration? |
|---|---|---|---|---|---|
| 1a | Adults | Blindfolded walking | Rate of visual motion | Real hallway | Yes |
| 1b | 12-year-old children | Blindfolded walking | Rate of visual motion | Real hallway | No |
| 1c | Adults | Blindfolded walking | Walking speed | Real hallway | Yes |
| 2a | Adults | Imagined walking | Rate of visual motion | Real hallway | Yes |
| 2b | 12-year-old children | Imagined walking | Rate of visual motion | Real hallway | No |
| 2c | Adults | Imagined walking | Walking speed | Real hallway | No |
| 3a | Adults | Imagined walking | Rate of visual motion | Virtual hallway | Yes |
| 3b | Adults | Imagined walking | Walking speed | Virtual hallway | No |

Table A2. Summary of the results of all eight experiments.

# APPENDIX B: FIGURES

Figure B1. Large-screen virtual environment set-up with treadmill and harness.

Figure B2. Virtual environment hallway (left) and real hallway (right).

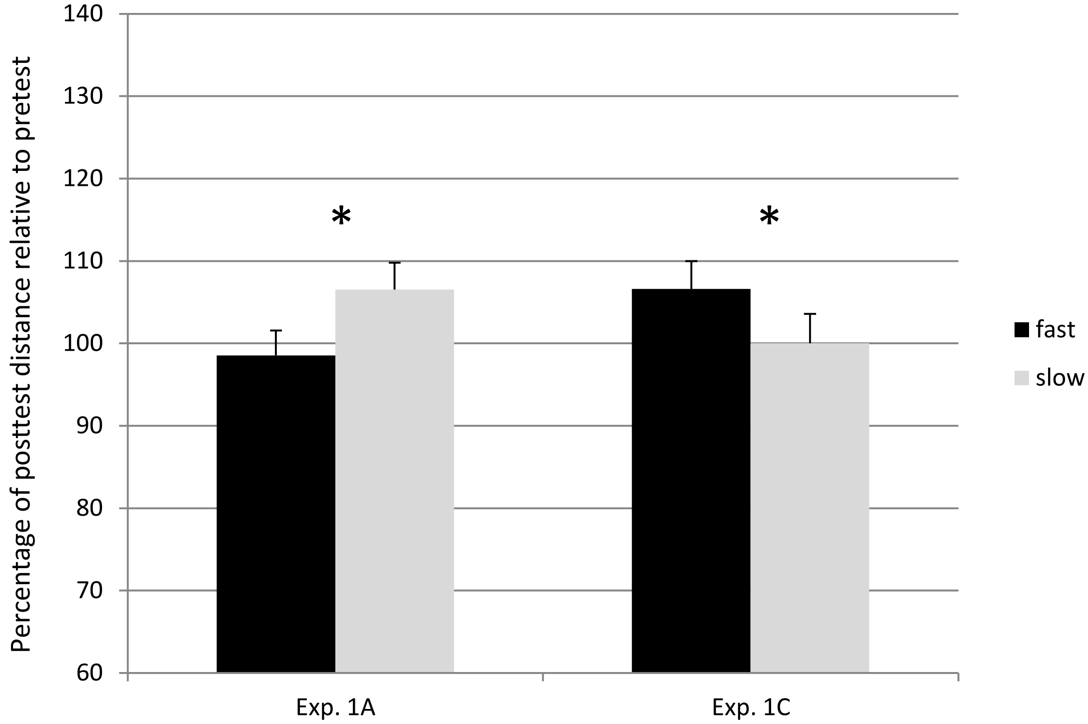


Figure B3. Percentage of distance estimated at posttest relative to pretest in the blindfolded walking task when manipulating visual motion (Experiment 1a) and walking speed (Experiment 1c).

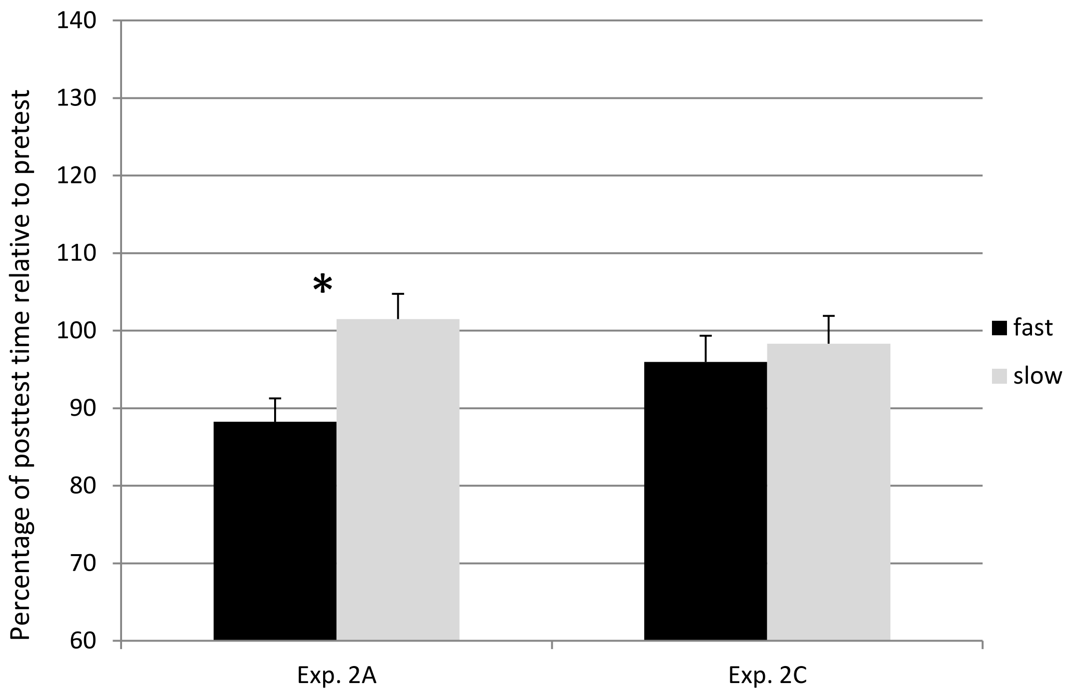


Figure B4. Percentage of distance estimated at posttest relative to pretest in the imagined walking task when manipulating visual motion (Experiment 2a) and walking speed (Experiment 2c).

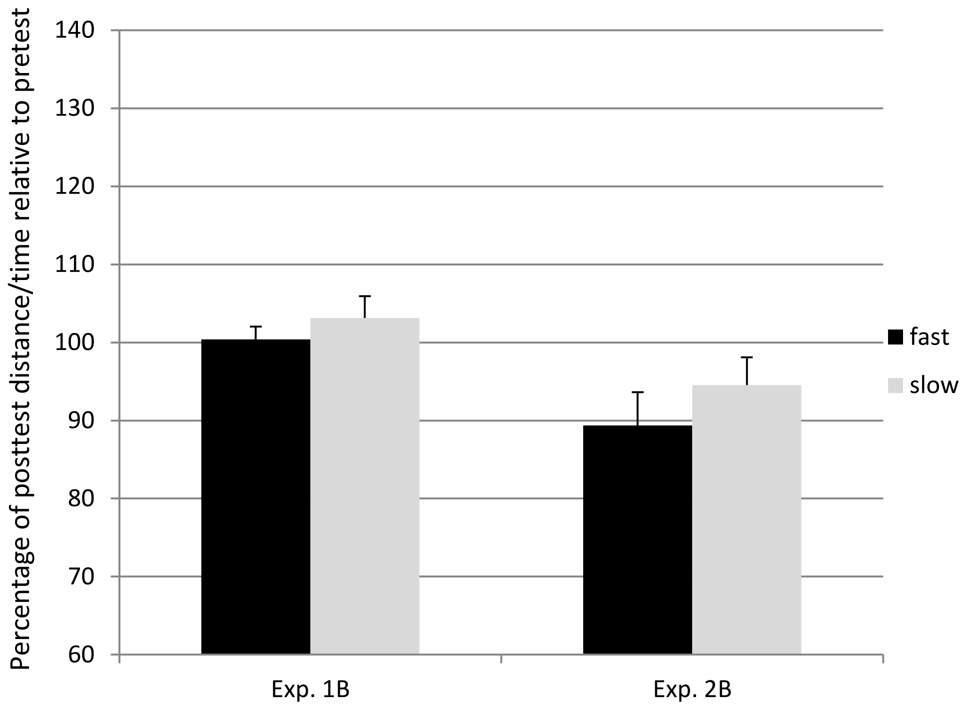


Figure B5. Percentage of distance estimated at posttest relative to pretest for 12-year-old children when manipulating visual motion in the blindfolded walking task (Experiment 1b) and imagined walking task (Experiment 2b).

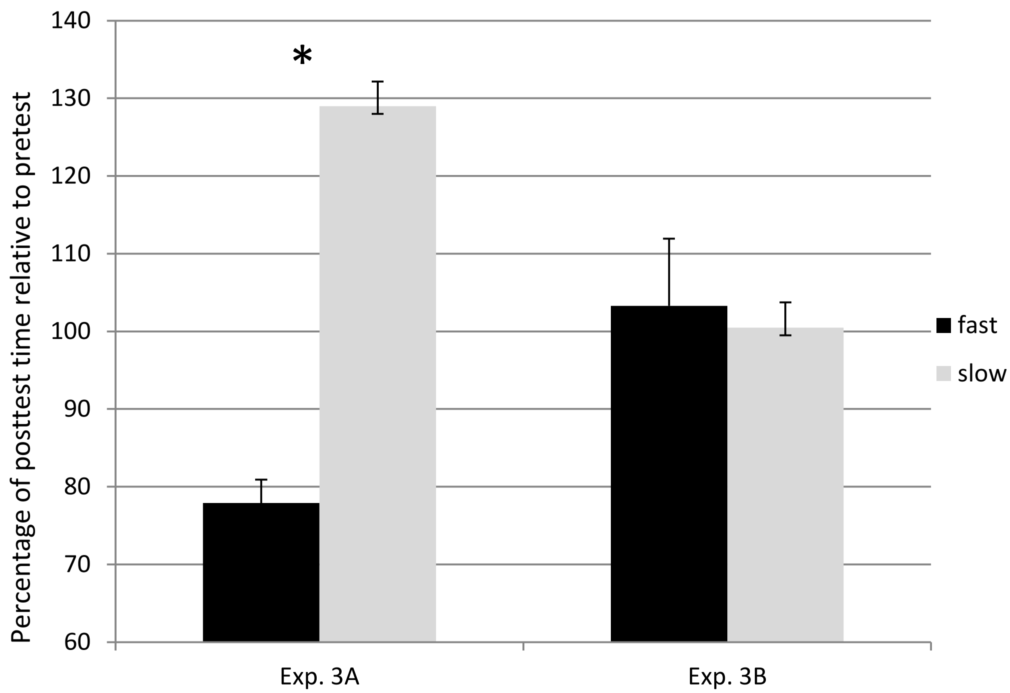


Figure B6. Percentage of distance estimated at posttest relative to pretest in the imagined walking task in a virtual environment when manipulating visual motion (Experiment 3a) and walking speed (Experiment 3b).

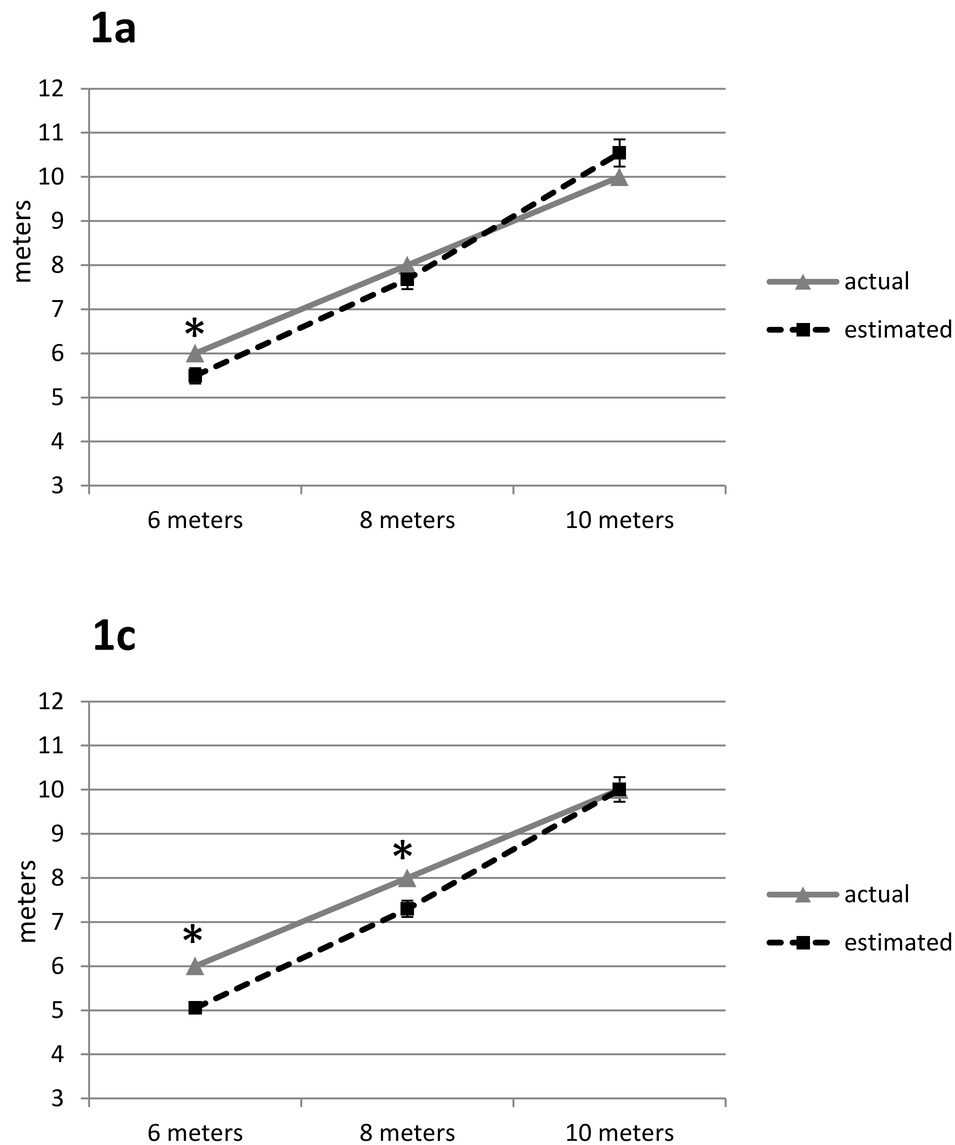


Figure B7. Pretest estimations compared to actual target distances for blindfolded walking task in Experiments 1a and 1c.

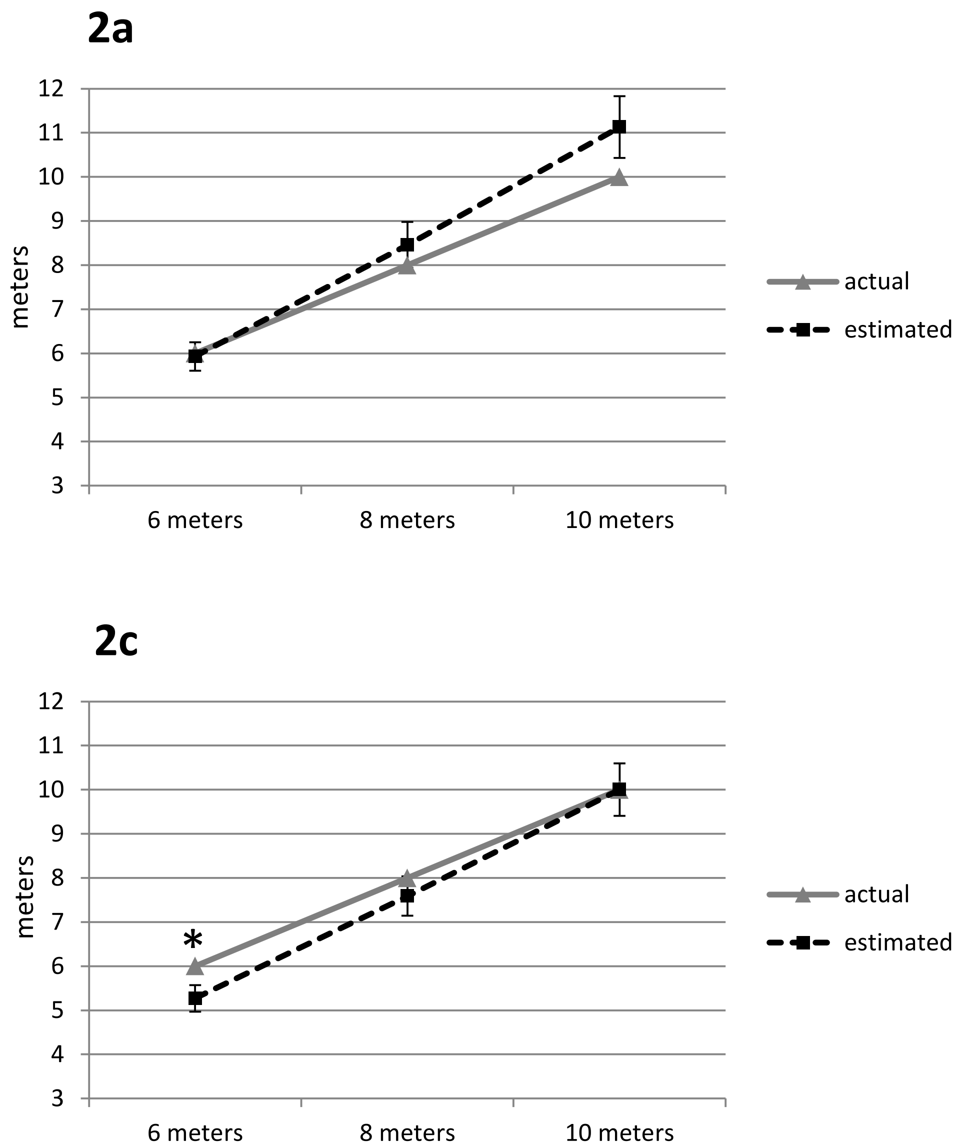


Figure B8. Pretest estimations compared to actual target distances for imagined walking task in Experiments 2a and 2c.

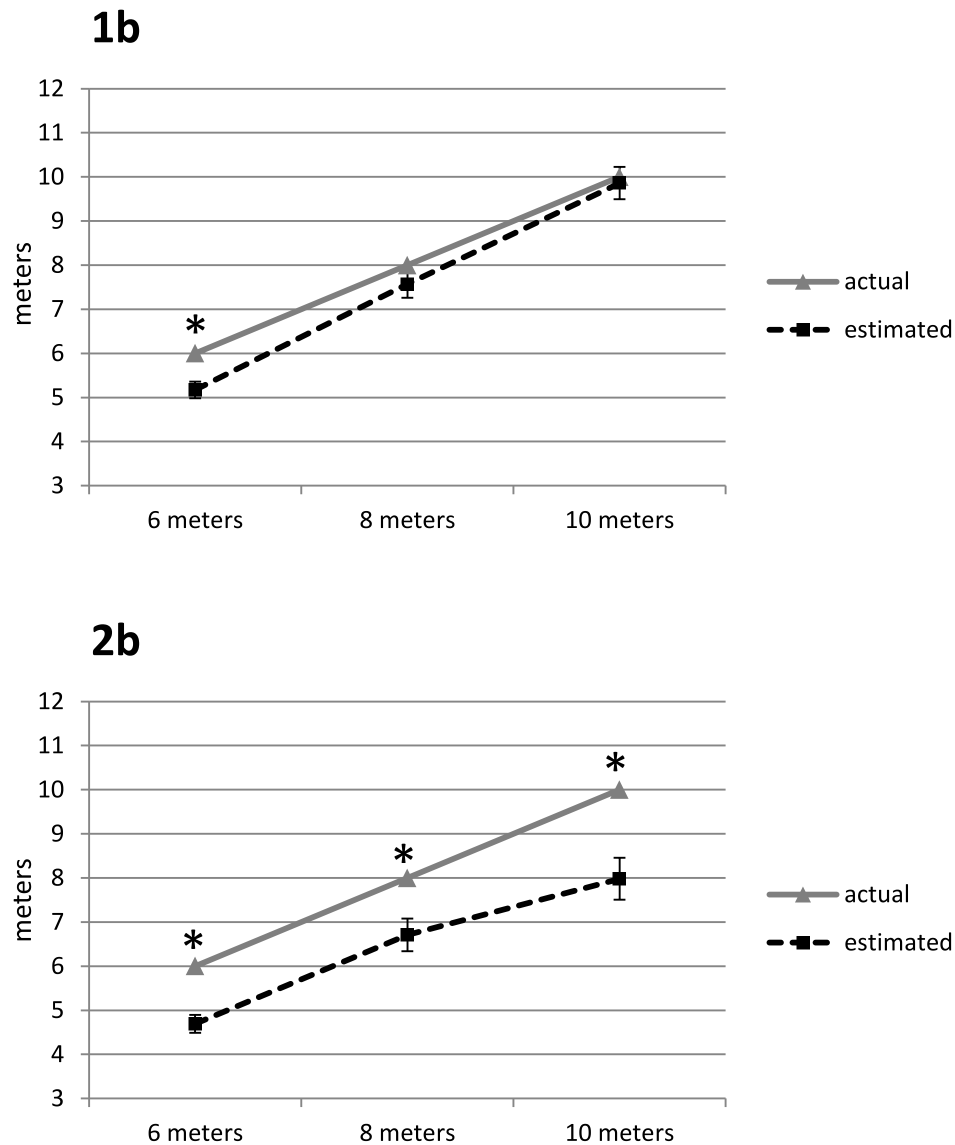


Figure B9. Pretest estimations compared to actual target distances with 12-year-old children in blindfolded walking task (Experiment 1b) and imagined walking task (Experiment 2b).

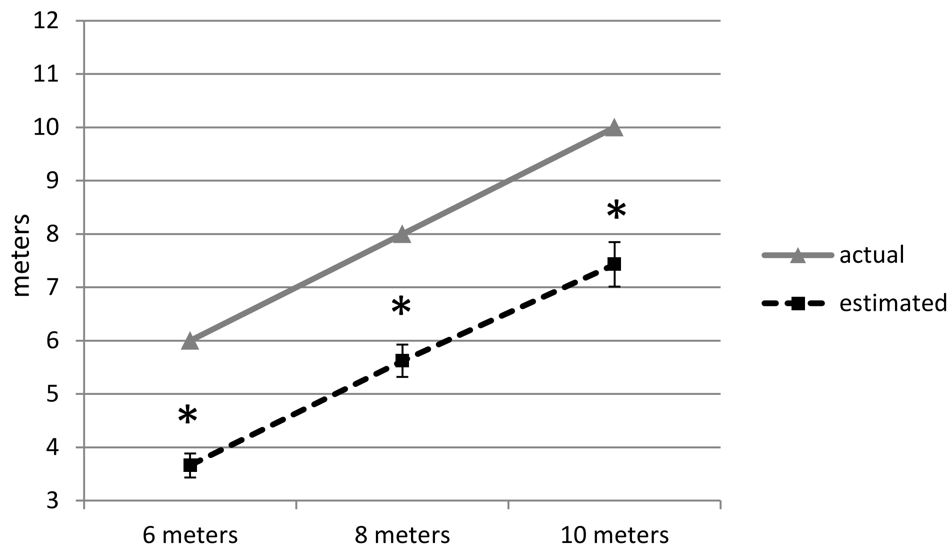


Figure B10. Pretest estimations compared to actual target distances for imagined walking task in a virtual environment (Experiment 3a).