Draft version 1 (28 September 2018). This paper has not been peer-reviewed.

Why is the Duration of Imagined Walking Underproduced?

A dual-representation view on the mental imagery of locomotion

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Word count: 14,712

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This research was supported by Queensland University of Technology Early Career Academic Recruitment and Development Grant, Cleveland State University Undergraduate

Research and Creative Achievement Award, and National Institutes of Health Grant R01 NS052137. The authors thank Serena Cristino, Thom Gennaro, Benjamin Lowe, and Alyssa Paredes for assistance with data collection.

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Abstract

Generally, imagining an action and physically executing it are thought to be controlled by common motor representations. However, imagined walking to a previewed target tends to be terminated more quickly than real walking to the same target, raising a question as to what representations underlie the two modes of walking. To address this question, the present study put forward a hypothesis that both explicit and implicit representations of gait are involved in imagined walking, and further proposed that the underproduction of imagined walking duration largely stems from the explicit representation due to its susceptibility to a general undershooting tendency in time production (i.e., the error of anticipation). Properties of the explicit and implicit representations were examined by manipulating their relative dominance during imagined walking through concurrent bodily motions, and also by using non-spatial tasks that extracted the temporal structure of imagined walking. Results showed that the duration of imagined walking subserved by the implicit representation was equal to that of real walking, and a time production task exhibited an equivalent underproduction bias as in imagined walking tasks that were based on the explicit representation. These findings are interpreted as evidence for the dual-representation view of imagined walking.

Keywords: simulated action, motor imagery, time production, error of anticipation, procedural memory

Public Significance Statements

This study examines how we imagine walking, a topic that has scientific and practical implications. Scientifically, investigation of the mechanisms of imagined walking promises to clarify the roles of conscious and unconscious processes in the control of actual walking, which

is fundamental to our well-being and survival. Practically, imagined actions have already been used for physical therapy and sports training, and refined knowledge about imagined walking helps increase the effectiveness of this method in these applications.

Why is the Duration of Imagined Walking Underproduced?

A dual-representation view on the mental imagery of locomotion

Imagining performing an action has been considered to activate motor representations of the action without moving relevant body parts (Annett, 1995; Jeannerod & Decety, 1995). This view has been posited on the basis that (a) the time it takes to imagine performing an action correlates with the time it takes to actually perform the action; and (b) manipulations that alter actual action (e.g., making a to-be-touched target narrower) tend to induce analogous changes in corresponding imagined action (Cerritelli, Maruff, Wilson, & Currie, 2000; Decety & Michel, 1989; Gentili, Cahouet, Ballay, & Papaxanthis, 2004; Kunz, Creem-Regehr, & Thompson, 2009; Radulescu, Adam, Fischer, & Pratt, 2010; Slifkin, 2008). These findings are interpreted as evidence that common representations are involved in actual and imagined action. The representations are likely to be motoric in nature, as opposed to propositional knowledge about the procedure and duration of an action (Kosslyn, Thompson, & Ganis, 2006; Pylyshyn, 1981, 2002), because the above-mentioned results are observed even when effects of the manipulations on actual action are not apparent to participants (Finke, 1979; Glover & Dixon, 2013). Moreover, imagining body movements and physically making the same movements often yield overlapping patterns of activation in the brain that include motor areas (Decety, 1996; Hamacher, Herold, Wiegel, Hamacher, & Schega, 2015; Jeannerod, 1995; la Fougère et al., 2010), further suggesting that mental simulation of action engages motor mechanisms that underlie actual execution of action.

Walking is one of the most fundamental actions that humans perform. A number of studies have been carried out to investigate mental simulation of walking, and results from these studies are consistent with the general findings summarized above: In overt behavior, the time it

takes participants to imagine walking a given distance varies systematically as a function of the walked distance (and thus as a function of the time it takes them to physically walk the same distance; Bakker, de Lange, Stevens, Toni, & Bloem, 2007; Courtine, Papaxanthis, Gentili, & Pozzo, 2004; Decety, Jeannerod, & Prablanc, 1989; Fusco et al., 2014; Papaxanthis, Pozzo, Skoura, & Schieppati, 2002; Personnier, Kubicki, Laroche, & Papaxanthis, 2010; Plumert, Kearney, Cremer, & Recker, 2005; Saimpont, Malouin, Tousignant, & Jackson, 2012; Schott & Munzert, 2007); and in the brain, movement-related areas such as the premotor cortex, supplementary motor area, and cerebellum are commonly activated while participants perform real and imagined walking (Bakker et al., 2008; Hamacher et al., 2015; Hanakawa et al., 1999; Harada, Miyai, Suzuki, & Kubota, 2009; Jahn et al., 2004; la Fougère et al., 2010; Miyai et al., 2001; van der Meulen, Allali, Rieger, Assal, & Vuilleumier, 2014). However, one notable observation is that participants often underproduce imagined walking times relative to real walking times that they spend actually walking the same distances (Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010; Kunz et al., 2009; Munzert, Blischke, & Krüger, 2015; Stevens, 2005). The degree of underproduction can be substantial, making the imagined walking times as short as 59% of the corresponding real walking times (Stevens, 2005). Such a considerable discrepancy between real and imagined walking times is puzzling—if common representations underlie real and imagined walking, why should they differ so much in duration? The goal of the present study was to address this question by clarifying what representations subserve imagined walking, and how they give rise to the underproduction of imagined walking times.

The first step of this investigation was to replicate the underproduction of imagined walking duration. Although multiple research groups independently found this pattern (Grechkin et al., 2010; Kunz et al., 2009; Munzert et al., 2015; Stevens, 2005), there are also studies in

which real and imagined walking times were comparable to each other (Bakker et al., 2007; Courtine et al., 2004; Decety et al., 1989; Fusco et al., 2014; Papaxanthis et al., 2002; Personnier et al., 2010; Schott & Munzert, 2007). Given this discrepancy in the literature, replication of the underproduction tendency would be crucial for the present study. It should be noted, however, that when imagined walking times were similar to real walking times, studies tended to contain additional factors that could have affected the duration of imagined walking. For example, Decety et al. (1989) showed equivalent walking times in real and imagined walking by specifically recruiting participants with good ability to create mental images (as determined by various mental imagery questionnaires; e.g., Sheehan, 1967) and instructing them to build a mental representation of a target and its surroundings prior to executing real and imagined walking. The participants' high imagery ability likely contributed to the equivalence of real and imagined walking times because a more general sample tested by Kunz et al. (2009) yielded imagined walking that was briefer than real walking despite following the same procedure as in the Decety et al. experiment. Similarly, van der Meulen et al. (2014) demonstrated that imagined walking times produced by good imagers closely matched their real walking times, whereas imagined walking times generated by poor imagers were shorter than their real walking times, even though the two groups did not differ in their real walking times (see also Corlett, Anton, Kozub, & Tardif, 1989, for similar results from real walking). Furthermore, it has been suggested that the duration of imagined action generally becomes longer as participants give more emphasis on the vividness of mental imagery (Guillot & Collet, 2005), and this effect is applicable to imagined walking as well—by specifically instructing participants to create the clearest possible motor images, Saimpont et al. (2012) showed that imagined walking times could even be longer than real walking times.

Schott and Munzert (2007) also adopted the procedure of the Decety et al. (1989) experiment, but with an important exception: Unlike in the Decety et al. study, participants in the Schott and Munzert study did real walking with eyes open. Although leaving the eyes open during walking might be more naturalistic, it made additional spatiotemporal cues available only to real walking (e.g., dynamic changes of landmark locations relative to self-position), introducing a major difference between real and imagined walking. This modification of the real walking procedure most likely had the effect of shortening real walking times as compared to those observed in eyes-closed real walking trials (Collins & Kuo, 2013; Koutakis, Mukherjee, Vallabhajosula, Blanke, & Stergiou, 2013). By contrast, it has been shown that the availability of static views of an environment during imagined walking does not affect the duration of imagined walking (Kunz et al., 2009; Plumert et al., 2005). Together, these findings suggest that by using eyes-open real walking, the difference between real and imagined walking times was decreased in the Schott and Munzert study.

Courtine et al. (2004), Fusco et al. (2014), Papaxanthis et al. (2002), and Personnier et al. (2010) found similar real and imagined walking times from non-specific young adult samples without particularly stressing the importance of vividness of motor imagery. Unlike the other experiments discussed here, however, participants in these studies were repeatedly exposed to one particular target distance only. This experimental design might have allowed the participants to learn the specific distance and match the temporal lengths of real and imagined walking well. In addition, as in the Schott and Munzert (2007) study, Courtine et al. and Personnier et al. had participants perform walking tasks with vision, and the same was likely the case in the studies by Fusco et al. and Papaxanthis et al. It is probable that the combination of these factors made the real and imagined walking times more similar to one another in these studies.

Finally, Bakker et al. (2007) also reported equivalent duration of real and imagined walking, but this study had two unique features. First, participants were always seated during imagined walking. It has been shown that imagined walking while sitting takes longer than imagined walking while standing (Saimpont et al., 2012). Second, participants in the Bakker et al. (2007) study performed imagined walking only by inspecting photographs of a hallway containing targets, whereas they carried out real walking by viewing the actual targets in the real hallway. Although it is not readily clear how exactly this difference affected real and imagined walking times, it is likely that participants' visual perception of target distance was different between the two modes of walking. As a result, it is not possible to determine whether the apparent similarity between real and imagined walking times indicated true equivalence of the duration of real and imagined walking.

In sum, there are factors that can make the duration of imagined walking similar to that of real walking: participants' high imagery ability, strong emphasis on the vividness of mental images, availability of vision during real walking, and possible learning effects during experiments. However, when these factors were minimized (e.g., by having non-specific participants walk and imagine walking multiple distances with their eyes closed), imagined walking times were clearly shorter than real walking times (Kunz et al., 2009). Thus, it is likely that the temporal underproduction is a basic property of imagined walking. The aim of Experiment 1 (and Supplementary Experiment) was to empirically confirm this notion in an imagined walking paradigm that was employed in the present study. After presenting this confirmation, this article reports experiments that investigated what representations imagined walking evokes and how they make the duration of imagined walking underproduced.

Theoretical issues relevant to this investigation are discussed later in the context of those experiments.

Experiment 1

The purpose of Experiment 1 was to confirm that underproduction of walking duration in imagined walking would be observed using experimental procedures of the present study.

Method

Participants. Thirty-six participants (18 men and 18 women, 18–63 years of age) were recruited at Cleveland State University and George Washington University. They participated in the experiment in return for monetary compensation or partial credit in psychology courses.

Participants in this and all subsequent experiments reported normal or corrected-to-normal vision and gave written informed consent to participate before commencing the experiments. Experimental protocols were approved by the Institutional Review Board of Cleveland State University, the Institutional Review Board of George Washington University, or the Human Research Ethics Committee of Queensland University of Technology, according to where each of the experiments was conducted.

Materials and design. While standing still, participants binocularly viewed a small orange cone (approximately 20 cm tall) on the floor of a hallway. The hallway at Cleveland State University was approximately 21 m long and 3 m wide, and the hallway at George Washington University was approximately 10 m long and 1.4 m wide. Both of the hallways had tiled floors. After briefly viewing the target cone, the participants either walked or imagined walking to it with their eyes covered with a blindfold and stopped when they judged that they had reached a remembered target location. The target was placed in front of the participants at 1, 2, 4, 6, or 8 m from their viewing position. The target distances were presented randomly with the constraint

that each distance was used four times per each walking mode. The time it took the participants to walk or imagine walking to the target was recorded in each trial. Physical distances walked by the participants were also measured in real walking trials. To discourage the participants from enumerating steps or seconds while performing real and imagined walking, they were given a sequence of five digits before starting to walk or imagine walking and asked to recall it upon completing a walking response. The digit sequence was randomly generated anew for each trial. This memory task was performed well (with 87% accuracy on average across all experiments), suggesting that it sufficiently interfered with mental counting. No performance feedback was provided throughout the experiment.

According to the order in which real and imagined walking trials were performed, three groups of participants were formed ($n = 12$ each, containing 6 men and 6 women). The first group executed a block of 20 real walking trials first and then moved on to the next block of 20 imagined walking trials (Real Walking First group). The second group also had real and imagined walking trials in blocks but in the opposite order (Imagined Walking First group). The third group received real and imagined walking trials randomly on a trial-by-trial basis (Random group). In previous studies, the order of real and imagined walking trials did not affect the difference between real and imagined walking times (Courtine et al., 2004; Kunz et al., 2009; Papaxanthis et al., 2002). Thus, it was predicted that all three groups of participants would yield shorter walking times in imagined walking than in real walking. Nevertheless, the trial order was manipulated because of the purpose of the present experiment: By finding underproduced imagined walking times using all three possible sequences of the trials, this experiment would unequivocally demonstrate the underproduction of imagined walking times.

For the same purpose, the present experiment involved two ways of instructing participants which task to perform in each trial, even though this manipulation has also been shown to have little or no impact on real and imagined walking times (Courtine et al., 2004; Kunz et al., 2009; Papaxanthis et al., 2002). In the Real Walking First and Imagined Walking First groups, participants knew whether they would walk or imagine walking in an upcoming trial because trials of the same type were blocked. On the other hand, in the Random group, participants were informed whether to walk or imagine walking only after viewing a target and covering their eyes. This procedure in the Random group was meant to strictly equate viewing experiences between real and imagined walking trials (Decety et al., 1989)—that is, in theory, participants can view a target differently depending on the type of walking to be carried out. By finding underproduced imagined walking times regardless of the two instruction procedures, it was intended that this experiment would firmly confirm the tendency of temporal underproduction in imagined walking.

The Real Walking First group was tested at George Washington University, and the other two groups were run at Cleveland State University. Thus, the groups differed not only in the task order but also in physical environments. Although the difference in the surroundings could have affected participants' visual perception of target distance (Lappin, Shelton, & Rieser, 2006), it was anticipated that effects of the environmental difference would not be critical because (a) the key comparison between real and imagined walking was done within-participant; and (b) temporal underproduction of imagined walking has been observed in multiple labs (Grechkin et al., 2010; Kunz et al., 2009; Munzert et al., 2015; Stevens, 2005).

Procedure. In the beginning of the experiment, participants were told that they would first view a small cone at various distances, and then they would either walk or imagine walking

to it while wearing a blindfold. For imagined walking, they were further instructed that they should imagine walking out into a hallway toward the cone in the same way as they would physically walk in real walking trials. The instructions contained an explicit statement that the participants should imagine walking in the same walking speed as they would use during the real walking trials. The participants viewed the target cone from the same location in all trials, from which they walked to the target in the real walking trials or performed imagined walking while standing motionless in imagined walking trials. The participants covered their eyes with the blindfold throughout the experiment except when they viewed the target from the viewing position. They also wore hearing protectors (with the noise reduction rating of approximately 20 dB) so that effects of external auditory cues on walking responses were minimized.

Real walking. Once positioned at the viewing location, participants lifted a blindfold and briefly viewed a cone that was placed at a target distance for a given trial. Subsequently, the participants covered their eyes again and walked to the remembered cone location. An experimenter removed the cone as soon as the participants put the blindfold back on. The experimenter stayed close to the participants throughout the trial for their safety, but their walking was unassisted. The experimenter activated a stopwatch when the participants began walking and stopped it when the participants ceased moving. Then the participants were guided back to the viewing location for the next trial without knowing the result of their walking response.

Before doing the first real walking trial, participants performed two practice trials using non-target distances of 3 and 5 m (once each). The practice trials followed the same procedure as described above. The order of the two practice trials was determined randomly for each participant. In the Imagined Walking First group, the practice real walking trials were given only

after all imagined walking trials were completed. In the Real Walking First group, the practice real walking trials were carried out at the beginning of the experiment. This was also the case in the Random group, but the practice real walking trials were intermixed with practice imagined walking trials (details are shown below).

Imagined walking. After viewing a cone and lowering a blindfold as in real walking trials, participants said aloud “start” when they imagined starting to walk out into a hallway, and “stop” when they imagined stopping at the cone. An experimenter measured the time interval between the two verbal markers by using a stopwatch. The participants remained at the viewing position throughout a trial.

Two practice imagined walking trials were performed in the same manner as in real walking. In the Real Walking First group, the practice imagined walking trials were not carried out until the real walking block was concluded. In the Imagined Walking First group, the practice imagined walking trials were given to participants at the outset of the experiment. In the Random group, all four practice trials (two for real walking and two for imagined walking) were presented in a block at the beginning of the experiment, in which the order of the four trials was randomly determined for each participant.

Power analysis. A priori power analysis was conducted (with the G*Power 3 program; Faul, Erdfelder, Lang, & Buchner, 2007) using $\eta_p^2 = .10$ as an estimated size of the main effect of walking mode (real and imagined) on walking times. This estimate was based on effect sizes reported in the literature—for example, when Kunz et al. (2009) and Munzert et al. (2015) had each participant perform real and imagined walking without any additional manipulations during imagined walking trials, the effect sizes of walking mode ranged from .12 to .84. To derive a conservative estimate of required sample size for the present experiment, a moderate correlation

($r = .50$) between real and imagined walking times was assumed. With these assumptions, the power analysis showed that the present experiment would detect the effect of walking mode with $\alpha = .05$ and $1 - \beta = .95$ by testing 33 participants in total (i.e., 11 participants per group).

Accordingly, the number of participants in this experiment was set at 12 per group (one participant was added for having the same number of male and female participants). For the sake of consistency, subsequent experiments in the present study tested 12 participants per group.

Figure 1. Mean walking times observed in Experiment 1 as a function of walking mode and target distance, collapsed over participants. Each error bar shows ± 1 standard error of the mean (SEM).

Figure 2. Mean walking times observed in Experiment 1 as a function of task order and walking mode, collapsed over participants. In the Real Walking First and Imagined Walking First groups, all trials using the same mode of walking were blocked. In the Random group, real and imagined walking trials were randomly intermixed in one block. Each error bar shows ± 1 SEM.

Results

Trials that yielded outliers—that is, walking times that were more than three standard deviations away from the mean—were excluded from analyses. The outliers were defined separately for each combination of task order (real walking first, imagined walking first, and random), walking mode (real and imagined walking), and target distance (1, 2, 4, 6, and 8 m). Twenty-four trials from six participants were removed, which constituted 1.7% of the total trials. Mean walking times for each participant were then calculated per task order, walking mode, and target distance, and analyzed by a 3 (task order) $\times$ 2 (walking mode) $\times$ 5 (target distance) mixed analysis of variance (ANOVA). Task order was a between-participant factor, and walking mode

and target distance were within-participant factors. Mean walked distances in real walking were computed in the same way, which showed that participants reached target locations with accuracy in all conditions (Rieser, Ashmead, Talor, & Youngquist, 1990; Thomson, 1983). For brevity, detailed analyses of walked distance data are reported in Supplemental Material. Data were also analyzed by including participants' gender as an additional between-participant factor in the ANOVAs, but there were no main effects or interactions involving gender ($F_s < 2.53$, $p_s > .08$, $\eta_p^2 < .15$). Thus, the data were collapsed over the gender variable. All ANOVAs conducted in this study were corrected for non-sphericity by the Greenhouse-Geisser method when appropriate.

Although the prediction tested in the present experiment was concerned with mean walking times (i.e., mean imagined walking times being shorter than mean real walking times), standard deviations of walking times were also computed and analyzed in the same way. These data represented the variability of participants' responses for a given target distance in each walking mode. This analysis did not yield outcomes of theoretical interest—the response variability enlarged as the target distance increased (as expected; see Kunz et al., 2009; Rieser et al., 1990), and the variability tended to be greater in later trials of the experiment. Importantly, these patterns were present irrespective of task order and walking mode. Thus, detailed analyses are reported only for mean walking time data.

Figures 1 and 2 display mean real and imagined walking times as a function of target distance and task order, respectively. These figures show that imagined walking times were shorter than real walking times across the board, suggesting that there was robust and systematic underproduction of imagined walking duration. This observation was confirmed statistically by the main effect of walking mode, $F(1, 33) = 33.19$, $p < .001$, $\eta_p^2 = .50$. The task order $\times$ walking

mode interaction was also significant, $F(2, 33) = 4.52, p = .02, \eta_p^2 = .22$, indicating that the degree of underproduction was modulated by the order of the tasks. However, as shown in Figure 2, imagined walking times were consistently shorter than real walking times in all three groups. Additionally, the main effect of target distance was significant, $F(4, 132) = 198.96, p < .001, \eta_p^2 = .86$, showing that real and imagined walking times lengthened as the target was farther away from participants. Finally, the walking mode $\times$ target distance interaction was also significant, $F(4, 132) = 10.36, p < .001, \eta_p^2 = .24$. The patterns of mean walking times in Figure 1 indicate that imagined walking times did not increase as much as real walking times did as target distance became longer.

Discussion

In Experiment 1, the duration of imagined walking was clearly underproduced relative to that of real walking. Although the degree of underproduction varied to some extent according to the order of real and imagined walking tasks, imagined walking times were consistently shorter than real walking times across all target distances (Figure 1) and all three groups (Figure 2). Importantly, in this experiment, extraneous factors that could make real and imagined walking duration similar (i.e., participants' high imagery ability, emphasis on the vividness of mental images, availability of vision during real walking, and possible learning effects due to the use of a single target distance) were either absent or reduced: The current participants were recruited in a non-selective manner; they were not specifically instructed to create mental images of the surroundings and targets; they had no vision while making a walking response; and they were exposed to multiple target distances randomly. Thus, results from this experiment confirm that when examined in an unbiased fashion, imagined walking to a previewed target is terminated more quickly than real walking to the same target.

In addition, this experiment was supplemented with Supplementary Experiment in which two additional groups of participants followed the same procedure with or without the concurrent memory task that required memorization of a random five-digit sequence during a walking trial. The purpose of Supplementary Experiment was to ensure that the concurrent memory task did not cause any major confounds, and there was indeed no significant difference between the groups in the way they performed real and imagined walking (i.e., imagined walking was shorter than real walking irrespective of the presence of the memory task). Not only does this finding rule out the possibility that the concurrent memory task biased results reported in this article, but also it gives further demonstration of the robustness of the underproduction of imagined walking duration, considering that alternative strategies (i.e., pace or second counting during walking) could have been possible when the memory task was not used. Details of Supplementary Experiment are available in Supplemental Material.

Experiments 2 and 3: Examining the Roles of Explicit and Implicit Representations in Imagined Walking

Findings from Experiment 1 empirically confirmed that walking times tend to be shorter in imagined walking than in real walking. Notably, this underproduction was robust—it occurred regardless of the order of the two tasks, and it persisted even when the use of alternative strategies such as counting steps or seconds during walking would have been possible (see Supplementary Experiment). With this confirmation in place, the following experiments examined why the duration of imagined walking is underproduced.

One key finding in the imagined walking literature is that marching in place during imagined walking makes imagined walking times comparable to real walking times (Kunz et al., 2009; see also Fusco et al., 2014). Kunz et al. interpreted this finding as evidence that imagined

walking is at least partially based on motor signals that underlie real walking. Moving legs provide afferent feedback that is consistent with biomechanical constraints of walking action, which should help calibrate motor commands for walking-related movements (Wolpert & Ghahramani, 2000). These better calibrated motor commands should make imagined walking more accurate, if the motor signals are indeed involved in imagined walking. To further demonstrate this point, Kunz et al. used another action (moving arms circularly) that was not part of natural ambulatory body motion and showed that performing this action concurrently with imagined walking had little effect on imagined walking times (i.e., they were underproduced as usual). These results suggest that only afferent information that is specifically relevant to walking can be useful for imagined walking, supporting the idea that the duration of imagined walking is determined by mentally performing walking using the motor signals.

Building upon Kunz et al.'s (2009) argument, Experiments 2 and 3 investigated what aspects of the marching action facilitated mental simulation of walking. On the one hand, it is possible that the primary role of physical steps in imagined walking was to make the rhythm of walking explicit to participants. In essence, in this view, rhythmic tactile feedback from the contact of each foot with the ground functioned in a way analogous to ticks of a metronome that help musicians set the tempo of music they play. This idea was tested in Experiment 2. On the other hand, the marching movements might have affected imagined walking mainly through implicit representations of walking action. According to this hypothesis, stepping in place activated procedural-memory representations of walking, which contributed to accurate generation of imagined walking times by providing information about the actual timing of ambulatory body movements. When participants stand still, this information is likely to be unavailable to explicit execution of imagined walking because the action timing is only

implicitly expressed in the procedural memory (Michon, 1990). Experiment 3 examined this hypothesis.

Experiment 2

As discussed above, it was hypothesized that marching movements would lead to accurate production of imagined walking times by making the rhythm of walking explicit. If this was true, then other methods of externalizing the rhythm should have similar effects, regardless of whether they are biomechanically consistent with ambulatory body motion. To test this idea, a group of participants in the present experiment clapped their hands during imagined walking such that the claps coincided with steps taken in their imagination. In addition, to replicate the previous finding of Kunz et al. (2009), another group of participants took steps in place during imagined walking. It was anticipated that real and imagined walking times would be equivalent in both groups.

Method

Participants. Twenty-four participants (5 men and 19 women, 17–32 years of age) were recruited at Queensland University of Technology. They either volunteered for the experiment or received partial credit in psychology courses in exchange for participation in the experiment.

Materials, design, and procedure. The experiment was carried out in a covered pathway that was approximately 19.8 m long and 1.2 m wide. The pathway had a flat concrete pavement with no patterns. Real and imagined walking trials were run in the same way as in Experiment 1 with a few modifications. First, because imagined walking duration was underproduced irrespective of the order of real and imagined walking tasks in Experiment 1, the task order was fixed in Experiment 2 such that a block of real walking trials was presented first, followed by a block of imagined walking trials. Second, target distances were 4, 6, 8, and 10 m

in this experiment, each of which was measured three times per walking mode. For practice trials, 5- and 7-m targets were used, once apiece for each mode of walking. Third, in the imagined walking trials, participants either clapped their hands so that the claps were synchronous to imagined steps (Synchronous Clapping; 3 men and 9 women) or made ambulatory leg movements without progressing through space (Marching; 2 men and 10 women). Other than the clapping or marching movements, participants did not make any additional body motions during imagined walking. Real walking was performed in a normal fashion (i.e., without any peculiar concurrent actions) in both groups.

Figure 3. Mean walking times observed in Experiment 2 as a function of walking mode and target distance, collapsed over participants. Data are shown separately for the two groups of participants who performed imagined walking while clapping their hands or marching in place. Target distances varied from 4 to 10 m in this experiment, and thus the range of the horizontal axes was adjusted accordingly. Each error bar shows ± 1 SEM.

Results

Outliers were defined for each walking mode and target distance using the same criteria as in Experiment 1. Two trials from one participant in the Marching group were removed from the data. Additionally, one trial in the Synchronous Clapping group was excluded from analyses because data were lost. They constituted 0.5% of the total trials. Mean walking times of each participant were then subjected to a 2 (concurrent action: synchronous clapping and marching) $\times$ 2 (walking mode) $\times$ 4 (target distance) mixed ANOVA. Concurrent action was a between-participant factor, and walking mode and target distance were within-participant factors.

Figure 3 shows mean walking times as a function of concurrent action, walking mode, and target distance. Results from the Marching group resembled those from the Kunz et al. (2009) experiment in which the same concurrent action was used—that is, imagined walking times were largely comparable to real walking times when participants took physical steps in place while imagining walking. On the other hand, contrary to the prediction, imagined walking times were still shorter than real walking times when participants clapped their hands synchronously with imagined steps. In the ANOVA, the main effect of concurrent action as well as the interaction between concurrent action and walking mode were absent, $F(1, 22) = 2.69, p = .12, \eta_p^2 = .11$ and $F(1, 22) = 0.99, p = .33, \eta_p^2 = .04$, respectively. These outcomes were consistent with the prediction. However, the main effect of walking mode was significant, $F(1, 22) = 4.67, p = .04, \eta_p^2 = .18$, indicating that imagined walking times were underproduced relative to real walking times. The patterns shown in Figure 3 suggest that this main effect was driven primarily by data from the Synchronous Clapping group: In this group, imagined walking times were consistently shorter than real walking times, but in the Marching group, a difference between real and imagined walking times, if any, was visible only at the 10-m target distance.

Thus, to gain deeper insights into the results, simple effects of walking mode were examined post-hoc in each group, despite the lack of the interaction between concurrent action and walking mode. These tests suggest that there was underproduction of imagined walking times in the Synchronous Clapping group, $F(1, 11) = 10.67, p = .008, \eta_p^2 = .49$, whereas real and imagined walking times were equivalent in the Marching group, $F(1, 11) = 0.44, p = .52, \eta_p^2 = .04$.

The ANOVA also revealed that the main effect of target distance as well as the interaction between walking mode and target distance were significant, $F(3, 66) = 336.93, p < .001, \eta_p^2 = .94$ and $F(3, 66) = 5.39, p = .02, \eta_p^2 = .20$, respectively. As in Experiment 1 and Supplementary Experiment, these results suggest that walking times became longer as targets were placed farther away, and this effect was less pronounced in imagined walking than in real walking (in the Synchronous Clapping group). There were no other main effects or interactions, $F_s < 1.46, p_s > .24, \eta_p^2_s < .07$.

Discussion

The present experiment tested the hypothesis that handclaps synchronous to imagined steps would effectively externalize the rhythm of walking, thereby allowing for accurate production of imagined walking times. Although results were not entirely clear-cut, there was sufficient evidence against the hypothesis: While the lack of the main effect of concurrent task and the interaction between concurrent task and walking mode did not constitute definitive evidence for the hypothesis, the significant main effect of walking mode was clearly contradictory to the hypothesis. Thus, it was reasonable to conclude that the physical steps of marching action during imagined walking were not merely to make the rhythm of walking available to explicit execution of simulated walking.

It is worth mentioning that data from the Marching group of the present experiment replicated the previous results of Kunz et al. (2009). In their experiment in which the same marching movements were performed during imagined walking, real and imagined walking times were virtually indistinguishable at 4-, 6-, and 8-m target distances. This was also the case in the current data (Figure 3B), reaffirming the effect of concurrent physical steps on imagined walking times. However, one thing to note is that at the 10-m target distance (which was not used by Kunz et al.), the mean imagined walking time might have diverged from the mean real walking time, suggesting that effectiveness of the marching movements could be restricted to relatively short distances. It remains to be seen whether the observed pattern was actually reflective of this possibility or simply noise in the data.

Experiment 3

Experiment 2 tested the idea that marching movements added an extra explicit input (i.e., the externalized rhythm of ambulatory steps) into mental simulation of walking. As shown above, no clear support for this idea was obtained in the previous experiment. By contrast, in Experiment 3, it was hypothesized that implicit representations of walking, which were presumably evoked by the marching movements, played a role in accurately setting the duration of imagined walking. If this hypothesis was true, then by increasing the salience of the implicit representations in controlling imagined walking performance, imagined walking times could become comparable to real walking times even in the absence of marching or any other walking-compatible bodily motions.

One way of making implicit procedural representations dominant in controlling an action is to shift the focus of attention away from the action itself (Beilock & Carr, 2001; Beilock, Carr, MacMahon, & Starkes, 2002; Wulf, McNevin, & Shea, 2001). For example, when expert golfers

putted while their attention was directed to an auditory target detection task in which they heard a series of tones and indicated the presence of a particular tone, their putting was more accurate compared to when they did the same putting while explicitly monitoring their swing (e.g., by specifying the moment at which the follow-through movement of a club reached its end; Beilock et al., 2002). Importantly, deterrence of focused attention on a primary task enhanced performance only when the task was well-practiced and therefore participants did not need to pay attention to its step-by-step procedure (Beilock et al., 2002; DeCaro, Thomas, Albert, & Beilock, 2011), suggesting that the effect of attention-dividing manipulation was to suppress explicit thinking about an action and thereby letting proceduralized representations of the action take over its execution. Given that bipedal locomotion is one of the best-practiced actions, it is highly likely that this theoretical framework applies to the control of walking. Thus, to achieve this effect in imagined walking, the clapping manipulation used in Experiment 2 was modified in the present experiment so that it would prevent participants from closely attending to explicit representations of walking. Specifically, the participants clapped their hands according to an externally given rhythm that was not synchronous to imagined steps. With this asynchronous handclapping, it was predicted that imagined walking times could be similar to real walking times.

Method

Participants. Twelve participants (3 men and 9 women, 17–29 years of age) took part in the experiment at Queensland University of Technology in exchange for partial credit in psychology courses.

Materials, design, and procedure. Real and imagined walking trials were carried out in the same manner as in Experiment 2 with the following change: During imagined walking,

participants listened to the sequence of tones that were not synchronous to natural timing of ambulatory steps, and were asked to clap their hands concurrently with each tone. Specifically, each tone (440 Hz) lasted for 100 ms, and two adjacent tones were separated by varying lengths of silence—they were 450-, 600-, and 300-ms long and repeated in this order. Over-the-ear headphones were used to present the tone sequence to the participants. The same headphones were worn during the real walking trials too so that they served as hearing protectors.

Results

One data point (constituting 0.3% of the data) was classified as an outlier and excluded from analyses by following the same procedure as in the previous experiments. Mean walking times of each participant were then analyzed by a 2 (walking mode) $\times$ 4 (target distance) within-participant ANOVA.

As summarized above, the hypothesis tested in this experiment was that asynchronous handclapping would make imagined walking times equivalent to real walking times. In other words, under this hypothesis, null effects of walking mode on walking times were expected in the aforementioned ANOVA. Because these null effects, even if observed, would not lend clear support to the hypothesis, Bayes factor analysis was also conducted for statistically assessing the degree to which the current data provided positive evidence for the null effects (Rouder, Morey, Speckman, & Province, 2012). Following the conventional guidelines, a Bayes factor of 3 or above would be taken as evidence in favor of the hypothesis (Kass & Raftery, 1995).

Figure 4 displays mean walking times as a function of walking mode and target distance. As clearly shown in the figure, real and imagined walking times closely resembled each other. There was neither a main effect of walking mode nor a walking mode $\times$ target distance interaction in the ANOVA, $F(1, 11) = 0.10, p = .76, \eta_p^2 = .01$ and $F(3, 33) = 0.88, p = .40, \eta_p^2 =$

.07, respectively. The main effect of target distance was significant, $F(3, 33) = 51.42$, $p < .001$, $\eta_p^2 = .82$, indicating that walking times increased as the distances to targets extended.

Two statistical models were contrasted in the Bayes factor analysis. One was the full model that included the main effects of walking mode and target distance as well as the interaction between the two. The other was a restricted model that had target distance as a sole factor. If this analysis favored the restricted model over the full model for describing the current data, it would suggest that all effects related to walking mode were negligible in this experiment. When the restricted model was compared against the full model in this analysis, it yielded a Bayes factor of 26.68, strongly supporting the conclusion that the absence of the effects of walking mode was real and not merely a consequence of a type-II error.

Figure 4. Mean walking times observed in Experiment 3 as a function of walking mode and target distance, collapsed over participants. Target distances varied from 4 to 10 m in this experiment, and thus the range of the horizontal axis was adjusted accordingly. Each error bar shows ± 1 *SEM*.

Discussion

Results from this experiment showed that imagined walking took as long as real walking did when participants clapped their hands asynchronously with imagined steps. Because this clapping action was not an intrinsic constituent of gait movements, the current finding suggests that the biomechanical consistency of marching action with ambulatory bodily motion was in and of itself not crucial for making the duration of imagined walking equivalent to that of real walking. Instead, it is more likely that activation of action timing implicitly represented in procedural memory of walking-related body movements was critical for the change in imagined walking times.

Importantly, this finding is not to refute the notion that motor simulation underlies imagined walking. Rather, it clarifies what information the mental simulation of walking needs in order to accurately set the duration of the simulation. In discussing this point, it is important to note that when imagined walking times changed in Experiments 2 and 3 (and also in the experiment by Kunz et al., 2009), they did not lengthen or shorten by an arbitrary amount but extended exactly to real walking times. To explain this rather specific change, an additional mechanism would need to be assumed, if the role of motor simulation in imagined walking were not postulated. Until the additional mechanism, if any, is identified, motor simulation aided by implicit representations of walking action remains to be a viable explanation for accurate production of imagined walking times in this and the relevant previous experiments.

Discussing the possible additional mechanism might be reminiscent of an alternative view that has been proposed in the literature: the so-called “tacit knowledge” account of imagery (Pylyshyn, 1981). According to this view, imagined walking times would not be based on motor simulation, but on participants’ knowledge about how long it should take to walk to a given

location. Although this view might be plausible in other contexts, it does not provide any simple explanations for the current findings—that is, it is not readily clear how participants' knowledge about the duration of imagined walking should be differently translated into overt production of imagined walking times depending on what concurrent actions they perform.

It may also be worth noting that the number-memory task (i.e., remembering the random sequence of five digits during an imagined walking trial) did not stop imagined walking duration from being underproduced in the previous experiments of the present study, even though this task could have interfered with explicit representations of walking to some extent. The lack of the effect of this task might simply mean that concurrent tasks have to be sufficiently salient to make implicit representations of walking dominant during imagined walking. Alternatively, it might indicate that the concurrent tasks need to involve some motor components in order to suppress explicit action representations. Distinguishing between these possibilities goes beyond the scope of this study. However, by clarifying conditions under which simultaneous execution of additional tasks eliminates the temporal underproduction tendency from imagined walking, the interplay between explicit and implicit representations may be more precisely characterized in future studies.

To conclude, Experiments 2 and 3 showed that proceduralized representations of walking action can make the duration of imagined walking equivalent to that of real walking. Because these are implicit representations in procedural memory, they need to be activated in some way, otherwise imagined walking is primarily based on mental representations of walking that can be explicitly conjured up in participants' mind. It appears that these explicit representations are particularly prone to the underproduction error—even though participants in Experiment 2 were made aware of when they were taking imagined steps in their explicit representations of walking,

it did not help them realize that they tended to terminate their imagined walking too soon. Thus, the next set of experiments investigated what properties the explicit representations have and how they give rise to the underproduction of imagined walking duration.

Experiments 4 and 5: Identifying the Origin of the Temporal Underproduction Tendency in Explicitly Executed Imagined Walking

In the previous experiments of the present study, target distances were visually perceived in the same way in real and imagined walking trials. Thus, it was reasonable to postulate that the duration difference between the two modes of walking was not ascribed to initial perception of the target distances. With this postulation, two hypotheses about the temporal underproduction error in imagined walking were formulated, focusing on possible biases in judgments of walking speed and time.

One hypothesis is that participants' imagined walking speed is faster than their physical walking speed (Speed Overestimation Hypothesis). In general, little physical effort is perceived while walking a short distance on a level surface, thanks to musculoskeletal properties of ambulatory body motions that minimize energy expenditure during walking. For example, average human walkers spontaneously select metabolically optimal step lengths and arm swings while walking (Collins, Adamczyk, & Kuo, 2009; Zarrugh, Todd, & Ralston, 1974). However, walking is still a metabolically expensive activity, requiring considerable energy when a landing leg makes contact with the ground (Malcolm, Derave, Galle, & De Clercq, 2013; Winter, 1983). It has also been suggested that walking consumes the greatest amount of energy among typical daily activities, indicating that its metabolic cost is not negligible (Collins, Wiggin, & Sawicki, 2015; Westerterp, 2013). Nevertheless, because walking is subjectively felt to be virtually effortless, it is possible that participants who imagine walking fail to take into account the energy

demand for physical bipedal locomotion, leading to overestimation of their walking speed and thus an underproduced temporal length of imagined walking.

A second, contrasting hypothesis is that typical imagined walking tasks, in which participants imagine moving toward a previewed target, are subject to a bias that causes premature termination of imagined walking. From a methodological point of view, these kinds of imagined walking tasks can be seen as time production tasks in which participants attempt to generate a time interval that matches a predetermined standard. In such time production tasks, there is a consistent tendency that while time intervals shorter than 1–2 s are produced accurately, longer intervals are systematically underproduced (Eisler, 1976; Ulbrich, Churan, Fink, & Wittmann, 2007; Wittmann, 2009). For example, Eisler (1976) conducted an extensive literature review and showed that when time intervals produced in these tasks are expressed as power functions of standard intervals, the exponents are often smaller than one. In other words, the produced intervals tend to increase more slowly than the standard intervals beyond the initial few seconds, leading to underproduction of intervals as the standard intervals lengthen.

This underproduction tendency could be attributed to the fact that time intervals can only be increased while they are being produced. For example, to produce a 10-s interval in a time production trial, participants must start at 0 s and wait until the interval increases to 10 s. In other words, it is not possible to take a 20-s interval and continuously reduce it to a 10-s interval—it would require a reversed flow of time, but time is perceived to run only from past to future (i.e., the property of psychological time referred to as the anisotropy of time; Riemer, 2015; Riemer, Trojan, Kleinböhl, & Hölzl, 2012). However, such unidirectionality is usually avoided in a task in which participants are to change the magnitude of a stimulus until it reaches a standard magnitude. Instead, participants both increase and decrease the magnitude of the stimulus to the

standard so that errors of anticipation (undershooting) and habituation (overshooting) are cancelled across trials (Baker, 1988; Grondin, 2016). For instance, when participants are asked to stop a moving object at a 10-m distance from them, in half the trials the object might start at the participants' feet and move away from them, and in the other half the object might be 20 m away from the participants in the beginning and move toward them. This way, the participants' inclination to stop the object too soon (or too late) would not bias the mean produced distance derived from both types of trials, assuming that the same kind of error (anticipation or habituation) is committed throughout the task. It is not possible to perform an equivalent manipulation in time production tasks. This constraint allows either anticipation or habituation errors to dominate in time production tasks, potentially causing overall underproduction or overproduction tendencies, respectively. The consistent underproduction of time intervals in the literature suggests that the error of anticipation is dominant in time production tasks (Eisler, 1976; Riemer, Rhodes, & Wolbers, 2016), and in turn, in imagined walking tasks. Accordingly, the second hypothesis is referred to as Anticipation Error Hypothesis hereafter.

Experiments 4 and 5 were designed to test these two hypotheses. It was important to distinguish between the hypotheses because they have different implications. To explain the temporal underproduction error in imagined walking, the Speed Overestimation Hypothesis posits a mechanism that is specific to imagined walking (or, perhaps more generally, imagined action in which minimal effort is perceived in actually doing the action). Thus, if true, this hypothesis suggests that the underproduction of duration stems from imagined walking itself. On the other hand, the Anticipation Error Hypothesis characterizes the underproduced duration of imagined walking as one manifestation of a general property of time production tasks. Under this hypothesis, the underproduction does not arise from imagined walking per se, but it is due to the

anisotropy of time that imposes the unidirectional nature on imagined walking trials. By contrasting the two hypotheses, the following experiments aimed to clarify whether it is the explicit mental image of walking itself or the temporal characteristic of the imagined walking trials that biases the produced duration of imagined walking.

Experiment 4

This experiment examined the Speed Overestimation Hypothesis, which posits that participants overestimate their walking speed in imagined walking, perhaps by not taking into account physical effort required for actual walking. To this end, participants in this experiment carried out real and imagined walking during a given time interval and estimated the distance, not time, that they walked. If the Speed Overestimation Hypothesis is true, overestimation of imagined walking speed relative to real walking speed should lead to greater estimates of walked distance in imagined walking than in real walking.

Method

Participants. Thirty-six participants (18 men and 18 women, 18–63 years of age) were recruited at Cleveland State University and George Washington University. They participated in the experiment in return for monetary compensation or partial credit in psychology courses.

Materials and design. This experiment followed the design of Experiment 1: There were two modes of walking (real and imagined) and three groups of 12 participants (6 men and 6 women) each who received real and imagined walking trials in blocks or randomly intermixed. Participants who performed the real walking block first were tested at George Washington University. The other two groups were run at Cleveland State University.

To test the Speed Overestimation Hypothesis, two major changes were made in the experimental design and procedure. First, instead of walking or imagining walking to a

remembered target location, participants in Experiment 4 commenced and terminated their walking according to experimenters' verbal commands ("start" and "stop"). The verbal commands were temporally separated by 1, 2, 4, 6, and 8 s, and as in target distances in Experiment 1, the time intervals were presented randomly with the constraint that each interval was used four times per walking mode. In real walking trials, the participants walked 1, 2, 4, 6, and 8 m during the above-specified intervals—in other words, they walked at the average speed of 1 m/s. Second, immediately after ceasing to walk or imagine walking, participants in Experiment 4 verbally estimated the distance they had just walked (either physically or imaginarily). The participants were allowed to express these estimates in any units of length, but they were instructed to use only one unit throughout the experiment and also to be as accurate as possible by using fractions as needed (e.g., "3.8 meters"). The participants performed the concurrent memory task as in Experiment 1, but they attempted to recall a memorized sequence of five digits only after giving a distance estimate.

Procedure. Prior to performing real and imagined walking trials, participants received training for the method of walking employed in this experiment. They were blindfolded and also asked to hold a bar horizontally by both hands. An experimenter pulled the bar so that the participants walked approximately at the 1 m/s pace. To achieve this, the participants were guided through the same linear path repeatedly until they walked it in an appropriate amount of time (e.g., 5 s for a 5-m path). The average walking speed was set at 1 m/s because this was a natural walking pace observed in a similar paradigm (Yamamoto et al., 2014). In addition to controlling the bar, the experimenter provided the participants with verbal feedback as necessary (e.g., "too slow") during this process. Once the participants familiarized themselves with the average walking speed of 1 m/s, they were told that it would be the rate of walking that they

would use during the experiment. Upon completion of this training, the participants were taken to a hallway in which the experiment was carried out.

Real walking. After briefly observing an empty hallway from the same viewing position as in Experiment 1, participants lowered a blindfold and held a bar horizontally by both hands. By pulling the bar, an experimenter had the participants walk over 1, 2, 4, 6, or 8 m in approximately 1, 2, 4, 6, or 8 s, respectively. The experimenter verbally provided the participants with “start” and “stop” commands to indicate the beginning and end of their walking. The experimenter measured the actual time spent for walking by a stopwatch and confirmed that there was no large discrepancy between intended and executed walking times—across all trials, the actual average walking speed was very close to the intended average speed of 1 m/s: $M = 0.98$ m/s, $SD = 0.10$ m/s. All other aspects of the real walking procedure remained unchanged from Experiment 1.

Imagined walking. As in real walking trials, participants briefly removed a blindfold and viewed the empty hallway before carrying out each imagined walking trial. Unlike in Experiment 1, an experimenter said aloud “start” and “stop” to mark out a time interval during which blindfolded participants imagined walking (by contrast, in Experiment 1, participants produced these verbal cues to indicate when they started and stopped imagining walking). Other than this difference, imagined walking was performed in the same manner as in Experiment 1. For practice trials, 3- and 5-s intervals were used.

Figure 5. Mean estimated walked distances in Experiment 4 collapsed over participants as a function of walking mode and time interval during which participants walked or imagined walking. Because participants walked at the average speed of 1 m/s in real walking trials, numbers on the horizontal axis can also be interpreted as indicating actual walked distances in meters. Thus, the diagonal (shown by the dashed line) represents accurate responses in real walking trials. Each error bar shows ± 1 SEM.

Results

Trials that yielded walked distance estimates that were more than three standard deviations away from the mean were excluded from analyses. These outliers were defined separately for each combination of task order, walking mode, and time interval. Twelve trials from six participants were removed in this manner, which constituted 0.8% of the total trials. Mean estimated walked distances for each participant were then calculated per task order, walking mode, and time interval, and analyzed by a 3 (task order) $\times$ 2 (walking mode) $\times$ 5 (time

interval) mixed ANOVA. Task order was a between-participant factor, and walking mode and time interval were within-participant factors.

Figure 5 shows mean estimated walked distances as a function of walking mode and time interval. Contrary to the Speed Overestimation Hypothesis, participants generated similar estimates of walked distances from real ($M = 3.24$ m, $SD = 1.12$ m) and imagined ($M = 2.93$ m, $SD = 1.25$ m) walking. In fact, distance estimates in imagined walking trials were reliably smaller, not larger, than those in real walking trials, $F(1, 33) = 10.60$, $p = .003$, $\eta_p^2 = .24$. This pattern was observed irrespective of task order: There was no main effect of task order or interactions including this variable, $F_s < 0.67$, $p_s > .52$, $\eta_p^2s < .04$. The main effect of time interval was significant, $F(4, 132) = 157.82$, $p < .001$, $\eta_p^2 = 0.83$, indicating that estimates of walked distances increased as the participants performed real and imagined walking during longer time intervals.

Discussion

Results from Experiment 4 contradicted the Speed Overestimation Hypothesis. Participants estimated that they had walked shorter distances in imagined walking than in real walking during the same time interval, indicating that walking speed was not overestimated in imagined walking. In fact, this pattern of distance estimates suggests that imagined walking speed was, if anything, underestimated.

These results indicate that there is no substantial bias in estimating walking speed in imagined walking. In addition, real and imagined walking trials are equated as to initial perception of a target distance in the current paradigm. Given the mathematical relationship between speed, distance, and time, a viable possibility is that time elapsed during imagined

walking provides a key to understanding why imagined walking duration is underproduced. The next experiment explored this idea.

Experiment 5

As discussed earlier, typical imagined walking, in which participants imagine walking to a previewed target, can be construed as a time production task. To focus on this aspect of imagined walking, Experiment 5 had participants carry out time production in a way that paralleled the imagined walking task in Experiment 1 but did not involve any spatial components. Participants in Experiment 1 were given spatial targets (e.g., a cone at a 4-m distance) and asked to produce times that they would need to mentally move to the targets. By contrast, participants in Experiment 5 verbally received temporal targets (e.g., “four seconds”) and generated time intervals that reached the specified lengths. As is often the case in time production tasks (Eisler, 1976; Riemer et al., 2012, 2016), it was predicted that these intervals would be underproduced in the present experiment. Consistent with Eisler (1976), this underproduction would be best described by expressing produced intervals as a power function of target intervals and finding an exponent smaller than one. If actually obtained, such a finding would suggest that imagined walking times are underproduced primarily because generation of time intervals is liable to the error of anticipation, supporting the Anticipation Error Hypothesis.

According to this explanation, it is specifically the error of anticipation, not any other characteristics of human time perception, that causes the temporal underproduction of imagined walking (Riemer & Wolbers, 2018). To demonstrate this specificity, Experiment 5 also used another temporal task in which the error of anticipation was removed by design. This removal was done by explicitly specifying the beginning and end of each time interval and having participants determine how long the interval was. In other words, this task resembled the

imagined walking task in Experiment 4, but it asked the participants to directly estimate the temporal extent of the given interval. Thus, the task was entirely within the temporal domain. If the underproduction of time intervals (including imagined walking times) was attributed to the error of anticipation, this estimation task should not find any similar foreshortening errors. On the other hand, if any unknown properties of time perception or tasks of the previous experiments were the true sources of the underproduction tendency, this task might find equivalent bias in the participants' time estimates.

Method

Participants. Twenty-four participants (3 men and 21 women, 17–51 years of age) were recruited at Queensland University of Technology. They either volunteered for the experiment or received partial credit in psychology courses in exchange for participation in the experiment.

Materials, design, and procedure. Each participant performed time production and estimation tasks. Half the participants (2 men and 10 women) did the time production task first, and the other half (1 man and 11 women) carried out the time estimation task first. They were seated in a quiet room and did not wear a blindfold and hearing protectors.

Time production. In each trial, participants were verbally provided with a time interval that they were to produce (e.g., “four seconds”), and clapped their hands twice so that the two claps were separated by the specified amount of time. An experimenter measured the time interval between the claps with a stopwatch. The participants also received a random sequence of five digits prior to the first clap and recalled it following the second clap. Five time intervals (1, 2, 4, 6, and 8 s), repeated four times apiece, were randomly given to the participants in a single block. Two practice trials using 3- and 5-s intervals were performed in advance of the experimental trials. No performance feedback was offered throughout the experiment.

Often, in time production tasks, to-be-produced standards are directly given as actual time intervals (e.g., by presenting a continuous sound that lasts for a given length of time), instead of indirectly specifying them by the numbers of seconds (Eisler, 1976; Riemer et al., 2012, 2016). The current experiment employed the latter method in order to conceptually replicate the imagined walking task in Experiment 1. That is, in the imagined walking trial, participants derived an appropriate amount of time to reach a target just by viewing it from the starting position, in the absence of direct time perception of the to-be-produced duration. Likewise, in the time production trial of this experiment, participants generated a time interval by mentally translating the number of seconds into an actual length of time, not by reproducing an immediate prior experience of explicitly perceiving the standard time interval.

Time estimation. In each trial, participants heard two 100-ms pure tones (440 Hz) that marked the beginning and end of a stimulus time interval. Subsequently, they verbally estimated the length of the presented time interval. The participants also received a random sequence of five digits prior to the first tone and recalled it after giving the verbal estimate of the interval magnitude. Five time intervals (1, 2, 4, 6, and 8 s), repeated four times apiece, were randomly given to the participants in a single block. Two practice trials using 3- and 5-s intervals were performed in advance of the experimental trials. No performance feedback was offered throughout the experiment. Presentation of the tones was controlled by the PsychoPy program (Peirce, 2007).

Figure 6. Mean produced and estimated time intervals observed in Experiment 5 as a function of stimulus time interval, collapsed over participants. The dashed diagonal line represents accurate production and estimation of time intervals in this experiment. Each error bar shows ± 1 SEM.

Results

Outliers were identified in the same way as in the previous experiments; that is, produced or estimated time intervals that exceeded or fell short of the mean by more than three standard deviations were removed from data. Three production trials from two participants as well as seven estimation trials from three participants were excluded from analyses. In addition, data were not recorded properly in three production trials due to equipment failure. Together, these trials constituted 1.4% of the total trials. Mean produced and estimated time intervals were then computed for each participant and for each stimulus time interval, and subjected to a mixed ANOVA in which task order (production first or estimation first) was a between-participant factor and task (production and estimation) and stimulus time interval (1, 2, 4, 6, and 8 s) were

within-participant factors. In addition, power functions were fit to the mean produced and estimated time intervals to evaluate whether the exponents of the power functions were smaller than one.

Figure 6 plots mean produced and estimated time intervals collapsed over participants as a function of stimulus time interval. Generally, the produced time intervals were shorter than corresponding stimulus intervals, whereas the estimated time intervals were longer than the corresponding stimulus intervals. In line with this observation, the main effect of task as well as the interaction between task and stimulus time interval were significant, $F(1, 22) = 6.06, p = .02, \eta_p^2 = .22$ and $F(4, 88) = 5.21, p = .03, \eta_p^2 = .19$, respectively. Data from the two groups of participants were somewhat dissimilar, as shown by the significant main effect of task order, $F(1, 22) = 4.46, p = .05, \eta_p^2 = .17$, and the significant interaction between task order and stimulus time interval, $F(4, 88) = 7.16, p = .002, \eta_p^2 = .25$. However, neither the task order $\times$ task interaction nor the task order $\times$ task $\times$ stimulus time interval interaction was significant, $F(1, 22) = 0.06, p = .82, \eta_p^2 = .003$ and $F(4, 88) = 0.16, p = .73, \eta_p^2 = .007$, respectively, indicating that task order did not affect the way the participants changed their responses according to stimulus time intervals. The main effect of stimulus time interval was also significant, $F(4, 88) = 827.95, p < .001, \eta_p^2 = .97$, showing that in both tasks response time intervals increased as stimulus time intervals lengthened.

To fit a power function to mean produced time intervals, a linear model was applied to log-transformed stimulus and produced time intervals, and the exponent and coefficient of the power function were derived from the slope and intercept of the best-fit linear model. The linear model described the log-transformed data well ($r^2 = .81$), and the exponent of the power function was estimated to be 0.86 (95% CI [0.78, 0.93]). As shown by the confidence interval, the

exponent was reliably smaller than one. The coefficient was estimated to be 0.96 (95% CI [0.86, 1.07]). These parameters indicate that in the range of stimulus time intervals used in this experiment, participants underproduced time intervals relative to the stimulus time intervals for the most part (Figure 6).

For comparison, we expressed imagined walking times in Experiment 1 as a power function of target distances in the same manner. The fit of a linear model to log-transformed data was good ($r^2 = .75$). The exponent of the power function was estimated to be 0.72 (95% CI [0.65, 0.78]), which was reliably smaller than one. The coefficient of this power function was estimated to be 2.00 (95% CI [1.83, 2.17]). Note that in this comparison, only exponents of power functions provide crucial information because coefficients vary according to absolute values of data. For example, by expressing the same data in a different measurement unit, the coefficient is altered. On the other hand, the exponent is invariant in such data transformation, capturing an essential relationship between independent and dependent variables. From this point of view, the two power functions reported above were very similar to each other.

Mean estimated time intervals were also expressed as a power function of stimulus time intervals in the same manner. The best-fit linear model described log-transformed data well ($r^2 = .75$), but the exponent of the power function was estimated to be 0.97 (95% CI [0.87, 1.08]), which was not reliably different from one. The coefficient of the power function was estimated to be 1.11 (95% CI [0.96, 1.28]). Thus, unlike in the time production task, there was no clear over- or underestimation tendency in the time estimation task.

Discussion

Participants in the present experiment exhibited clear underproduction of time intervals in the absence of walking or any other spatial components in the time production task. In addition,

the way the participants underproduced the time intervals in this experiment was very similar to how participants in Experiment 1 underproduced imagined walking times—when produced times in these tasks were expressed as power functions of stimulus intervals (given by either spatial targets or the numbers of seconds), they yielded comparable exponents. This similarity suggests that the underproduction of imagined walking times can be largely accounted for by temporal, as opposed to spatial, characteristics of the imagined walking task. Namely, the duration of imagining walking can only be increased while it is being produced, making it susceptible to an undershooting bias (i.e., the error of anticipation). In sum, these results are consistent with the Anticipation Error Hypothesis.

When the error of anticipation was excluded from a temporal task (i.e., the time estimation task), no substantial bias was observed in participants' estimates of the intervals of one to eight seconds. This result suggests that the error of anticipation makes a unique contribution to the underproduction tendency in time production tasks, lending further support to the Anticipation Error Hypothesis about imagined walking.

It is worth noting that the unbiased estimates of time intervals observed in the time estimation task rule out another possible explanation of the underproduction tendency in time production: One could simply assume that one subjective unit of time is shorter than one objective unit of time. With this assumption, underproduction of time intervals can be predicted—for example, when a task is to produce an interval of eight objective seconds, participants spend eight subjective seconds, which are briefer than eight objective seconds. Although this explanation might sound more parsimonious than the Anticipation Error Hypothesis that is based on the anisotropy of time, the alternative explanation does not coherently account for the data of the present study because the discrepancy between

psychological and physical time should have caused distinct overestimation in the time estimation task. For instance, when a task was to receive an interval of eight objective seconds and estimate its length, more than eight subjective seconds should have elapsed during the objective interval, generating an overestimate of the objective interval. However, as summarized above, no clear overestimation occurred in the time estimation task. Moreover, a shorter subjective unit of time relative to an objective unit of time should have resulted in overestimated walking speed, and in turn, overestimated walked distance in imagined walking in Experiment 4. This pattern was not found either. Taken together, just assuming a shorter subjective unit of time does not fully explain the temporal underproduction of imagined walking.

General Discussion

Being prompted by the observation that the duration of imagined walking is often underproduced relative to the corresponding duration of real walking (Grechkin et al., 2010; Kunz et al., 2009; Munzert et al., 2015; Stevens, 2005), the present study was conducted to investigate what mental representations underlie imagined walking, and what properties these representations possess. It has been proposed that doing a real action and mentally simulating it involve common representations (Annett, 1995; Jeannerod & Decety, 1995). However, the degree of the underproduction of imagined walking duration can be substantial (e.g., Stevens, 2005), calling for investigation as to how such a large discrepancy can arise from the common representations.

After reaffirming that imagined walking duration is underproduced irrespective of the order of the real and imagined walking tasks (Experiment 1) and the presence of a concurrent memory task that discouraged counting during walking (Supplementary Experiment), this investigation was carried out in two steps in the present study. First, by capitalizing on marching

movements that have been shown to make the duration of imagined walking comparable to that of real walking (Kunz et al., 2009), Experiments 2 and 3 examined whether explicit or implicit information about the temporal structure of walking action made critical impact on imagined walking performance. In Experiment 2, externalization of the rhythm of gait using handclaps synchronized with imagined steps did not alter the underproduction of imagined walking times. On the other hand, in Experiment 3, diversion of participants' attention from imagined body movements through the act of handclapping asynchronous to the imagined steps, which presumably increased the salience of proceduralized representations of bipedal locomotion in imagined walking, led to generation of imagined walking times that were equivalent to real walking times. These results suggest that the timing of ambulatory steps implicitly represented in procedural memory would be crucial for accurately setting the duration of imagined walking.

Second, having found that the underproduced duration of imagined walking primarily stems from the explicit aspect of imagined walking, two hypotheses were formulated about possible mechanisms of the underproduction. The Speed Overestimation Hypothesis posited that participants would overestimate their walking speed in imagined walking due to failure in properly accounting for energy expenditure associated with physical locomotion. Participants in Experiment 4 did not estimate their walked distances to be longer in imagined than in real walking during the same duration, rejecting this hypothesis. The Anticipation Error Hypothesis postulated that as a time production task, imagined walking would be susceptible to the error of anticipation, and this temporal characteristic of the task would be a primary cause for the underproduction of imagined walking times. In Experiment 5, when the temporal aspect of imagined walking was extracted and carried out as a stand-alone time production task, the pattern shown by produced time intervals mirrored the pattern of imagined walking times

observed in Experiment 1. In addition, this result did not generalize to the time estimation task, another temporal task in which the anticipation error was prevented. These results supported the Anticipation Error Hypothesis. Taken together, findings from Experiments 4 and 5 put forward the view that it is the general property of psychological time (i.e., the anisotropy of time), not imagined walking itself, that makes participants terminate their responses prematurely in imagined walking trials.

Interrelation between Spatial, Temporal, and Motor Aspects of Imagined Walking

One notion that emerges from the current findings is that imagined walking cannot be well understood by focusing on its motor or temporal aspects alone. On the one hand, Kunz et al. (2009) argued that imagined walking times were underproduced because of the lack of coincident motoric signals that were consistent with ambulatory bodily motion, and the key data that supported this argument—imagined walking times being equivalent to real walking times when participants marched in place during imagined walking—were replicated in the present study. Meanwhile, Experiment 5 of the present study demonstrated that the error of anticipation as occurring in the temporal domain could explain the underproduction of imagined walking times to a large extent. These views, which attempt to interpret imagined walking performance solely from a motor or temporal perspective, offer reasonably good explanations for why the duration of imagined walking tends to be shorter than that of real walking. On the other hand, the present study revealed limitations of those views as well. In Experiment 3, imagined walking times were made comparable to real walking times by using another concurrent action (i.e., asynchronous handclapping) that did not provide any gait-related afferent feedback, suggesting that it was not the motoric signals per se that changed imagined walking times in the marching experiments (Kunz et al., 2009; and also Experiment 2 of the present study). Results from

Experiments 2 and 3 also showed that the duration of imagined walking could not vary freely when it was altered, but instead it was still constrained by the corresponding duration of real walking, which was determined by the actual processing of ambulatory motoric signals. As such, the duration of imagined walking was not entirely independent of the effects of the motoric signals. Taken together, the current results point to the possibility that for full characterization of the (dis)similarity between real and imagined walking, it would be necessary to establish a new framework in which the motor and temporal aspects of imagined walking are jointly considered. This framework is yet to be fully specified, but it has already put forth one concrete idea in the present study—that is, the timing of body movements implicitly expressed in the motoric signals can play a crucial role in controlling the duration of imagined walking. This idea should be further developed for attaining a deeper understanding of imagined walking and its motor-time characteristics.

In addition to the motor and temporal aspects, imagined walking has one more distinct aspect: It is a spatial task too in that responses are typically directed toward spatially defined targets (as in Experiments 1–3), and even in the absence of such targets, a spatial dimension is clearly implicated in the task because participants are to mentally displace themselves to a new location (as in Experiment 4). In all of these experiments, the main effects of traveled distance were sizable and accounted for the largest portion of variances. Indeed, it is the spatial aspect that gives the defining characteristic of the task. After all, the task is about how far participants go in an imaginary space, and how long they spend imagining walking is relevant primarily as a means of making the psychologically traveled distance measurable. Thus, in developing a new theoretical framework for explaining real and imagined walking duration, the spatial aspect also needs to be taken into consideration.

The need of considering spatial and temporal aspects together has been raised in research on self-motion perception. When participants were first transported passively over a given linear distance while seated in an electric wheelchair and then asked to reproduce the distance by controlling the wheelchair by themselves, they performed the task not just by focusing on the traveled distance, but by replicating the velocity profile that they experienced during the initial travel (Berthoz, Israël, Georges-François, Grasso, & Tsuzuku, 1995; Israël, Grasso, Georges-François, Tsuzuku, & Berthoz, 1997). The fact that the velocity profile was replicated even though it was not necessary (i.e., the task was to reproduce the distance) suggests that the spatiotemporal dynamics of the travel was mentally represented as a unified whole. Similarly, when blindfolded participants paced out a stimulus path and attempted to replicate its distance by walking in various speeds, they yielded optimal performance using an equal walking speed for both encoding the stimulus distance and making a response (Mittelstaedt & Mittelstaedt, 2001). In addition, biasing perception of one of the two aspects of self-motion tends to induce corresponding change in perception of the other aspect. For example, when perceived duration of walking was altered by using a mental arithmetic task known to interfere with perception of temporal intervals, reproduced walked distance also changed accordingly (Glasauer, Schneider, Grasso, & Ivanenko, 2007). These findings suggest that distance and duration of whole-body displacement are closely interrelated in the perceptual representations of self-motion. In this manner, there is a rich accumulation of data about this issue in the domain of real self-motion, and it is an important challenge to transfer the knowledge to the research on imagined self-motion.

This transfer would entail in-depth contrast of the ways in which the dynamic space-time relationship is represented in real and imagined walking because the underproduction of

imagined walking duration strongly suggests that this relationship is differentially expressed in the two modes of walking. To this end, a seminal study was conducted by Campos, Siegle, Mohler, Bühlhoff, and Loomis (2009) in which participants kept extending their arm toward a fixed object while they passed or imagined passing by the object. The arm angle in pointing to the object was continuously monitored, from which moment-by-moment changes of perceived and imagined self-location along a travel path were derived. This method allowed for direct comparison of the velocity profiles of real and imagined walking, instead of just measuring their distance and duration as in traditional paradigms. Campos et al. showed that the velocity profiles indeed differed between real and imagined walking. Specifically, in real walking, the angular velocity of arm movement increased as participants moved closer to the object, reached the maximum when they were directly to the side of the object (i.e., when the arm was perpendicular to the travel path), and decreased as they moved away from the object. This velocity profile reflected the ideal pattern of pointing. On the other hand, in imagined walking, the maximum velocity was not observed at the ideal point, and the change of velocity before and after the peak was not as systematic as in real walking (e.g., the arm rotated at a constant speed for a while before it started decelerating). Although it is not yet clear what exactly these observations have revealed about imagined walking, the potential of this new approach is evident. Future research should build on this initial study and investigate how perceptual space and time are differently interrelated in real and imagined walking.

Explicit and Implicit Representations in Real and Imagined Walking

The present findings indicated the presence of explicit and implicit representations in imagined walking. In typical imagined walking tasks in which participants' mind is not filled with any particular salient mental events (e.g., Experiments 1 and 2), production of time intervals

is presumably carried out by retrieving explicit memories for how body parts are moved during walking in general and also for how these movements were made while walking to the same targets in previous real walking trials (when they are available). On the other hand, when participants' attentional resources are directed away from imagining walking (e.g., Experiment 3), produced time intervals clearly differ from those observed in the typical imagined walking tasks, suggesting that the intervals are generated through different processes. Assuming that participants' attention is largely devoted to cognitive operations other than conjuring up a mental image of walking, it follows that imagined walking times produced under this condition stem from implicit, procedural-memory representations of walking action.

Results from the present study suggest that it is important to distinguish between the roles of explicit and implicit representations in imagined walking because they show several distinct characteristics. First, while imagined walking times based on the explicit representations are underproduced, imagined walking times based on the implicit representations are accurate. Therefore, the temporal underproduction tendency should be defined specifically as a property of explicit imagined walking, not that of imagined walking in general. It is possible that due to the inaccessibility of the implicit representations to conscious processing, imagined walking duration generated from them is relatively immune to perceptual and cognitive biases including the error of anticipation. Second, under normal circumstances, imagined walking is primarily driven by the explicit representations. By contrast, for the implicit representations to take control of imagined walking, it is necessary to either purposely attenuate the predominance of the explicit representations through attentional manipulations or directly activate the implicit representations by concurrent actions that are consistent with ambulatory body movements.

The distinction between explicit and implicit representations that underlie imagined walking also provides a clue for understanding why real walking is not susceptible to the error of anticipation in the same way as imagined walking. In real walking trials, blindfolded participants always approach a previewed target from one direction. In other words, walked distance in a given trial only increases to the remembered target location (unless participants take back steps or turn around to move in the opposite direction during the trial, neither of which happened in the present study). Thus, just like imagined walking times, real walked distances (and therefore real walking times as well) could be subject to the anticipation error. However, as shown in Figure S2 in Supplemental Material, participants accurately reached targets in this study (and also in previous studies that used similar paradigms; e.g., Rieser et al., 1990; Thomson, 1983). This might seem contradictory on the surface, but it should be noted that with the marching and asynchronous handclapping actions, the effect of the anticipation error was removed in imagined walking. This change in imagined walking times was explained by postulating that implicit representations of ambulatory body movements predominated over explicit representations of them in controlling imagined walking under these conditions. Thus, the fact that real walking is relatively free from the anticipation error suggests that the implicit representations activated by actual execution of gait are dominant in real walking too, allowing participants to execute the right amount of walking. In this manner, distinguishing the roles of explicit and implicit representations of bipedal locomotion can be useful for analyzing not just imagined walking but also real walking.

The above argument might bring to mind the theory about two streams of visual information processing in the brain: the dorsal stream for action guidance and the ventral stream for object perception (Milner & Goodale, 1995). Generally, actual contents of the dorsal stream

processing are not available to consciousness, but accurately executed actions that result from them demonstrate their presence (e.g., Goodale, Milner, Jakobson, & Carey, 1991). On the other hand, the ventral stream processing gives rise to conscious recognition of perceived objects and it is often susceptible to various perceptual biases (e.g., Aglioti, DeSouza, & Goodale, 1995). Thus, the notion of dual representations that underlie ambulatory movements—implicit representations that allow for accurate walking to a target and explicit representations that are liable to the error of anticipation—is consonant with the theory. As discussed previously, results from the present study support this notion. In addition, Wraga, Creem, and Proffitt (2000) put forward a similar idea by showing that biasing visually perceived locations of targets using an optical illusion did not alter participants' responses when they paced out distances to the targets, but did affect them when they verbally reported the same distances. These behavioral data from tasks involving walking are consistent with the two-stream theory, which has largely been developed by using action and perception within peripersonal space (e.g., reaching and grasping). However, it should be pointed out that existing neuropsychological data from similar walking paradigms do not necessarily conform to the theory. Patients with parietal lesions (i.e., damage to the dorsal stream) exhibited intact performance in walking to a previewed target without vision (Philbeck, Behrmann, Black, & Ebert, 2000), and those who had undergone surgery to resect their right anterior medial temporal lobe (which has strong connections with the ventral stream; Kravitz, Saleem, Baker, Ungerleider, & Mishkin, 2013; Suzuki & Naya, 2014) did show deficits in this task (Philbeck, Behrmann, Levy, Potolicchio, & Caputy, 2004; Yamamoto et al., 2014). Therefore, although the present results might fit well with the two-stream theory, it is still an open question whether the theory in its current form is applicable to the control of walking and perception of a spatiotemporal extent that goes beyond arm's reach.

Relationship with Other Types of Imagined Action

The Anticipation Error Hypothesis explains the underproduction of imagined walking times just by referring to the error of anticipation that is present in time production in general. Although this generality can be a potential appeal of the hypothesis, it is yet to be incorporated into the hypothesis because for its simplest (and thus the strongest) version to be upheld, any imagined actions that can be construed as time production tasks must show the same kind of underproduction of imagined movement duration relative to corresponding real movement duration. However, counterexamples to this prediction can be found in the literature. For instance, imagining reaching and touching a visually defined target by hand can take longer, not shorter, than actually performing the same action (Cerritelli et al., 2000; Glover & Dixon, 2013). Thus, currently, the Anticipation Error Hypothesis needs to be narrowly defined as an account of imagined walking duration alone, even though the hypothesis in the current form does not contain anything that constrains its scope specifically to imagined walking. Explaining why and how the effect of the anticipation error can be uniquely present (or, at least, particularly pronounced) in imagined walking would be an important next step toward fully understanding the role of the anticipation error in imagined walking and possibly in other imagined actions.

Conclusions

Why is the duration of imagined walking so underproduced relative to that of real walking, even though it has been postulated that common representations subserve both modes of walking? The present study provided one possible answer to this question. The underproduction of imagined walking duration is not a universal property of imagined walking, but it is specifically caused by explicit representations of walking action that play a large part in typical imagined walking tasks. Humans possess implicit representations of walking as well, in

which the timing of ambulatory body movements is accurately expressed. When activated, these implicit representations can override the explicit representations and thus remove the underproduction tendency. Because activation of the implicit representations can easily be done (either by actually doing the walking action or by shifting attention away from the explicit mental image of walking), the duration underproduction may rarely come out to the full extent in everyday situations.

In answering the above question, the present study revealed the intricate relationship between spatial, temporal, and motor aspects of imagined walking. It is evident that each aspect plays a prominent role in imagined walking, but none of them solely accounts for the duration of imagined walking. Instead, there is complex interplay between the three aspects, through which the length of imagined walking time is determined. Findings from this study identified some of the possible ways this interaction takes place, and they also offered several potential directions in which further research on this issue can be conducted. For example, measuring a velocity profile of imagined walking through the continuous pointing paradigm (Campos et al., 2009) would be a fruitful approach. Given the current findings, however, this approach should come with careful analysis of methodology. Importantly, it should be clarified first whether the continuous pointing action activates explicit or implicit representations of ambulatory body movements because depending on which is the case, outcomes of this new research have different implications. The data provided in the present study furnish a solid empirical basis on which these problems can be explored in the future.

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