

Motor imagery of gait: a quantitative approach

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Received: 15 August 2006 / Accepted: 14 November 2006
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Abstract Motor imagery (MI) is widely used to study cognitive aspects of the neural control of action. Prior studies were mostly centred on hand and arm movements. Recently a few studies have used imagery tasks to explore the neurophysiology of human gait, but it remains unclear how to ascertain whether subjects actually perform imagery of gait as requested. Here we describe a new experimental protocol to quantify imagery of gait, by behaviourally distinguishing it from visual imagery (VI) processes and by showing its temporal correspondence with actual gait. Fourteen young healthy subjects performed two imagery tasks and an actual walking (AW) task. During both imagery tasks subjects were sitting on a chair and faced a computer screen that presented photographs of walking trajectories. During one task (MI), subjects had to imagine walking along the walking trajectory. During the other task (VI), subjects had to imagine seeing a disc moving along the walking trajectory. During the

AW task, subjects had to physically walk along the same walking trajectory as presented on the photographs during the imagery tasks. We manipulated movement distance by changing the length of the walking trajectory, and movement difficulty by changing the width of the walking trajectory. Subjects reported onset and offset of both actual and imagined movements with a button press. The time between the two button presses was taken as the imagined or actual movement time (MT). MT increased with increasing path length and decreasing path width in all three tasks. Crucially, the effect of path width on MT was significantly stronger during MI and AW than during VI. The results demonstrate a high temporal correspondence between imagined and AW, suggesting that MI taps into similar cerebral resources as those used during actual gait. These results open the possibility of using this protocol for exploring neurophysiological correlates of gait control in humans.

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Keywords Motor imagery · Visual imagery ·
Gait · Fitts' law · Neuroimaging

Introduction

Motor imagery (MI) has been defined as mentally simulating a given action without actual execution (Jeannerod 1994). It has been shown that imagining a movement relies on neural processes similar to those evoked during real performance of the same movement (Porro et al. 1996; Stephan et al. 1995; Lang et al. 1994; Deiber et al. 1998; Roth et al. 1996). Accordingly, MI allows one to identify cognitive and cerebral properties of movement representations independently

from motor output and sensory feedback (de Lange et al. 2005). However, this strength might become a weakness when the experimental design does not allow for a quantification of imagery performance. This issue appears to be particularly relevant for imagery studies dealing with the neurophysiology of human gait (Jahn et al. 2004; Malouin et al. 2003; Miyai et al. 2001). Differently from the extensive work done on imagery of hand and arm movements (Decety and Michel 1989; Johnson-Frey 2004; Parsons 1987, 1994), it remains unclear how to ascertain whether subjects actually perform imagery of gait. The issues of task compliance and performance are particularly important when studying patient populations. Accordingly, in this study we aim at developing a quantitative approach to MI of gait. Our goal is to have an experimental setting in which it is possible to quantify imagery of gait, and to study the neurophysiology of gait in patient populations without the potential confounds of altered motor output or sensory input.

One approach that has been used to quantify task performance during an imagery task involves the use of mental chronometry (Guillot and Collet 2005). Mental chronometry refers to inferring the time course of information processing in the nervous system (Donders 1969). It has been demonstrated that a close temporal correspondence exists between actual and imagined movements. For example, it takes approximately the same time to write or to imagine writing a short sentence (Decety and Michel 1989). In addition, it has been demonstrated that both true and imagined movements conform to Fitts' law (Decety and Michel 1989). This law, originally obtained in the context of manual aiming movements (Fitts 1954), describes the inverse and logarithmic relationship that link the difficulty of a movement and the speed with which the movement can be performed. For instance, when target size decreases during a manual pointing task, movement difficulty increases and movement speed decreases (Sirigu et al. 1996). Because of the close temporal correspondence between true and imagined movements, imagined movement times (MTs) have been used to monitor task performance. A close temporal correspondence would suggest that subjects were able to perform the MI task. However, it should be noted, that there continues to be some opposition to the notion that imagined MTs can serve as proof that subjects performed the task. It has been argued that the close temporal correspondence may be attributable to a subject's tacit knowledge about the time it takes to actually execute the movement (Pylyshyn 2002).

In this study we capitalize and elaborate on recent reports showing that both actual and imagined walking

conforms to Fitts' law (Decety 1991; Decety and Jeannerod 1995; Stevens 2005). In these studies, subjects were asked to walk or to imagine walking towards a certain spatial target. Movement distance was manipulated by positioning the target at different distances from the subjects. Movement difficulty was manipulated by asking subjects to walk along beams of different widths (Stevens 2005; Decety 1991), or towards doors of different widths (Decety and Jeannerod 1995). These studies showed that, during performance of both real and imagined movements, walking times increased with increasing movement distance and difficulty. However, it remains unclear how to use these insights in an experimental setting that would allow one to study not only behavioural responses, but also neurophysiological variables. For example, the study of Stevens (2005) used a single trial procedure in an ecologically valid environment; that is, during the imagery trial the subject was physically standing in front of the same path used for the walking trial. This task feature might be crucial, as it may be difficult to adequately estimate distance and width of a walking trajectory from a two-dimensional display. On the other hand, the experimental set-up of Stevens (2005) is not immediately compatible with the experimental constraints (averaging over multiple trials, impoverished experimental environment) that are imposed when measuring neurophysiological variables, like during functional magnetic resonance imaging (fMRI) or transcranial magnetic stimulation (TMS) experiments. Decety and Jeannerod (1995) circumvented some of these problems by having subjects immersed in a virtual reality environment, but it remains unclear whether such an experience is crucial for evoking MI. Accordingly, we have elaborated on the study of Stevens (2005) and adapted it to a neuroimaging setting. In this report we describe this new experimental protocol, and we examine whether we can replicate the behavioural finding described in Stevens (2005).

Methods

Fourteen healthy right-handed subjects (seven men; age 22 ± 2.8 years, mean \pm SD) participated after giving written informed consent according to institutional guidelines of the local ethics committee.

Experimental settings

There were three linoleum gait trajectories (length = 12 m; thickness = 3 mm). Each trajectory (or path) had a different width (PATH WIDTH—9, 18, and

27 cm). The path width of 27 cm allowed subjects to easily walk over the path with a normal gait (Fig. 1a). The path width of 18 cm forced subjects to carefully walk over the path, given the narrow base of support. The path width of 9 cm forced the subjects to walk even more carefully over the path, given the very narrow base of support which approximately equalled the width of a single foot. The beginning of the walking trajectory was marked by a green square (64 cm^2). The end of the walking trajectory was marked by a green pillar (diameter—7.5 cm, height—12 cm) which could be placed at five different distances from the green square along the path (PATH LENGTH—2, 4, 6, 8, and 10 m). We made photographs of each of the different walking trajectories (PATH WIDTH (three) \times PATH LENGTH (five) = 15 walking trajectories—Fig. 1a). In addition, we made photographs of each walking trajectory with a black disc (diameter—7.5 cm, height—2.5 cm) replacing the green square at the beginning of the walking trajectory (Fig. 1b). This resulted in a total of 30 photographs. Stimuli presentation and behavioural response were controlled through a PC running Presentation software (Neurobehavioral Systems, Albany, USA).

Tasks

There were two experimental sessions, an imagery session and an actual walking (AW) session. During the imagery session subjects performed two imagery tasks: MI and visual imagery (VI). During both imagery tasks, subjects were sitting on a chair, facing a computer screen positioned at a distance of 65 cm. Each trial started with the presentation of a photograph of a walking trajectory. During MI trials, a green square was present at the beginning of the path

(Fig. 1a), and subjects had to imagine walking along the path. During VI trials, a black disc was present at the beginning of the path (Fig. 1b), and subjects had to imagine seeing the disc moving along the path. The trial time course for both MI and VI trials was as follows. Subjects could inspect the photograph on display, for as long as they wanted, then closed their eyes and imagined standing left to the path, next to the green square (MI trials) or the black disc (VI trials). They were then instructed to press a mouse button with the index finger of their right hand to signal that they had started the imagery trial, i.e. they imagined stepping onto the path and walking along the path (MI trials), or imagined seeing the disc moving along the path (VI trials). The subjects were then instructed to press the mouse button again when they imagined that they had reached the end of the walking trajectory (MI trials), or that the disc had reached the end of the walking trajectory (VI trials). During both tasks the end of the walking trajectory was marked by a green pillar. After subjects had pressed the button they opened their eyes and a fixation cross was presented on the screen until the onset of the next trial (inter-trial interval, 1–2.5 s). Subjects performed both imagery tasks with their eyes closed, and the time between the two button presses was taken as imagined MT.

Subjects performed the two imagery tasks in separate blocks; block order was counter-balanced across subjects. Each condition [i.e. PATH WIDTH (three levels) and PATH LENGTH (five levels)] was repeated six times, generating a total of 90 trials in each block, with a pseudo-randomized trial order. The imagery session was preceded by an induction phase, in which we presented subjects the three actual paths. Subjects were instructed to pay attention to the width and length of the paths, but were not allowed to walk along

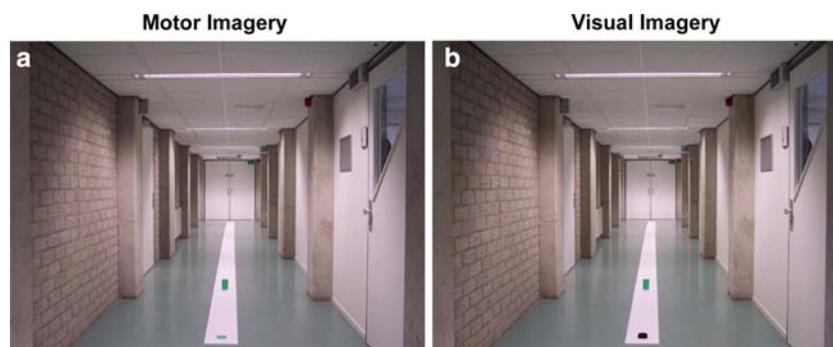


Fig. 1 Examples of photographs of walking trajectories presented to the subjects during the **a** motor imagery (MI), and **b** visual imagery (VI) experiment. Both photographs show a corridor with a path in the middle and a green pillar positioned on the path. During MI trials, a green square is present at the

beginning of the path. During VI trials, a black disc is present at the beginning of the path. In these examples, the path width is 27 cm, and the pillar is placed at a distance of 2 m from the beginning of the path. While these examples are shown in grey scale, the photographs were presented to the subjects in colour

them. Instead subjects were asked to walk three times along short versions (2 m) of each of the three path widths, prior to the MI block. This was done to make subjects familiar with the feeling of walking along each of the different path widths. A drawback of this AW experience is that it gives subjects tacit knowledge about the time it takes to walk along the different paths, which they might use to solve the imagery task. We used short versions of each of the paths to minimize this problem as much as possible. Subjects were instructed to walk along the paths at a comfortable pace, and they were instructed not to place their feet outside the path. Subjects were explicitly instructed to imagine walking along the paths in a first-person perspective, and to imagine as if their own legs were moving. In addition, they were instructed not to make any actual movements. Prior to the VI block, subjects were familiarized with the disc used in the VI trials, and they were informed that the disc moved autonomously, in a straight line and could not move outside the path.

After the imagery session, subjects performed the AW session. The AW session was always performed after the imagery session to minimize the amount of tacit knowledge about the time it takes to actually walk along the walking trajectories during the MI task. During the AW session, subjects physically walked barefoot along the same paths displayed during the imagery session. The subjects were instructed to walk at a comfortable pace, and they were instructed not to place their feet outside the path. Each condition [i.e. PATH WIDTH (three levels) and PATH LENGTH (five levels)] was repeated two times, generating a total of 30 trials, with a pseudo-randomized trial order. Each trial started with the subject standing left to the path, next to a green square placed at the beginning of the path (Fig. 1a). Then, they were instructed to step onto the path and to walk along the path until they reached the green pillar marking the end of the walking trajectory. As the subjects began and ended the movement, they started and stopped a stopwatch held in their hand. The experimenter recorded the time (MT). The subjects did not see the recorded MTs during the experiment.

Data analysis

We investigated the effect of TASK (AW, MI, VI), PATH LENGTH (2, 4, 6, 8, 10 m), and PATH WIDTH (9, 18, and 27 cm) on MT. We also looked at effects of task ORDER (MI–VI–AW, VI–MI–AW) to investigate possible carry-over effects from one task to the next. The significance of the experimental factors was tested within the framework of the General Linear Model using a

$3 \times 5 \times 3 \times 2$ repeated measures ANOVA. When interactions were significant, the simple main effects were investigated by additional repeated measures ANOVAs. The alpha-level of all behavioural analyses was set at $P < 0.05$, univariate approach. Greenhouse–Geisser corrections were applied to ensure that the assumption of sphericity was met, resulting in adjusted P -values based on adjusted degrees of freedom. In addition, we examined whether MT obtained in each task conformed to Fitts' law:

$$MT = a + b \log_2(2 * \text{path length}/\text{path width}).$$

In the equation, a and b are constants. The term $\log_2(2 \times \text{PATH LENGTH}/\text{PATH WIDTH})$ is called the index of difficulty (ID). It describes the difficulty of the motor tasks. We calculated ID for each of our 15 experimental conditions [i.e. PATH WIDTH (three levels) and PATH LENGTH (five levels)]. Several of the conditions had the same ID value. For each task and each subject, the MT of these conditions was averaged. Fitts' law states that MT increases linearly with increasing ID. We therefore examined how well MT conformed to Fitts' law by calculating the linear regression of MT over ID for each task and for each subject separately. Finally, we examined whether the degree to which MT conformed to Fitts' law was different for the different tasks, by considering the effect of TASK (AW, MI, and VI) on r^2 after z -score transformation using a repeated measures ANOVA.

Results

We found no significant differences in MTs between the three tasks [TASK: $F_{(2,24)} = 1.1$, $P = 0.356$ —Fig. 2a]. In all three tasks, MT increased with increasing path length [main effect of PATH LENGTH: $F_{(1,1,12,9)} = 93.02$, $P < 0.001$; MI ($F_{(1,0,12,5)} = 30.0$, $P < 0.001$); VI ($F_{(1,2,14,0)} = 32.3$, $P < 0.001$); AW ($F_{(1,3,15,8)} = 1,297.4$, $P < 0.001$)—Fig. 2b], and with decreasing path width [main effect of PATH WIDTH: $F_{(1,1,13,3)} = 28.4$, $P < 0.01$ —Fig. 2c]. However, the effect of path width on MT differed for the different tasks [TASK \times PATH WIDTH interaction: $F_{(2,2,26,5)} = 3.8$, $P = 0.032$]. The effect of path width was greater for AW than for VI [$F_{(1,2,13,8)} = 4.9$, $P = 0.040$], and for MI than for VI [$F_{(1,3,15,5)} = 6.5$, $P = 0.016$], and it was not significantly different between MI and AW [$F_{(1,1,13,4)} = 0.4$, $P = 0.578$]. Additional analysis demonstrated that MT significantly increased with decreasing path width during both MI [$F_{(1,1,13,5)} = 16.4$, $P = 0.001$] and AW [$F_{(1,1,12,8)} = 34.3$, $P < 0.001$], whereas there was a trend

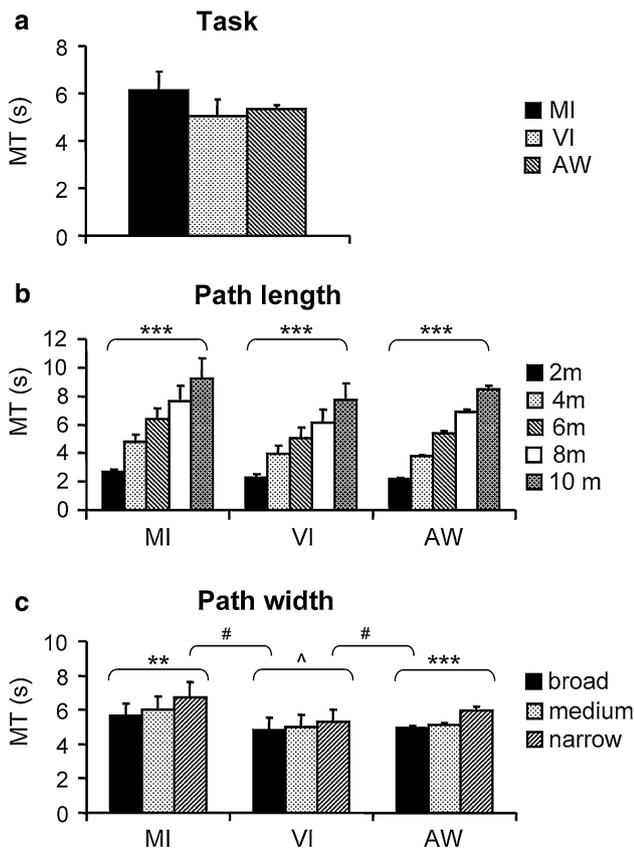


Fig. 2 Movement times (*MTs*) are shown for **a** each of the three tasks [motor imagery (*MI*), visual imagery (*VI*), and actual walking (*AW*)], **b** for the five different path lengths (2, 4, 6, 8, and 10 m) separately for each task, and **c** for the three different path widths [broad (27 cm), medium (18 cm), and narrow (9 cm)] separately for each task. Data represent mean \pm SEM. *** $P < 0.001$, ** $P < 0.01$, $\wedge P = 0.054$ (effects of path length and path width on *MT* for each task separately), # $P < 0.05$ (differential effect of path width on *MT* across the different tasks)

that *MT* increased with decreasing path width during *VI* [$F_{(1.2,14.2)} = 4.2$, $P = 0.054$].

The effect of path width on *MT* was not influenced by the order in which the different tasks were performed [PATH WIDTH \times ORDER interaction— $F_{(1.1,13.3)} = 1.0$, $P = 0.388$; TASK \times PATH WIDTH \times ORDER interaction— $F_{(2.2,26.5)} = 0.3$, $P = 0.743$]. The effect of path width on *MT* differed for the different path lengths [PATH WIDTH \times PATH LENGTH interaction— $F_{(2.6,31.0)} = 17.6$, $P < 0.001$], such that the effect of path width increased with increasing distance (Fig. 3).

Movement time correlated linearly with *ID* in each of the three tasks (Fig. 4a). However, the r^2 of this correlation was different for the different tasks [main effect of TASK: ($F_{(2,26)} = 6.1$, $P = 0.007$)—Fig. 4b]. The r^2 was greater for *MI* than for *VI* [$F_{(1,13)} = 12.8$, $P = 0.003$], and for *AW* than for *VI* [$F_{(1,13)} = 6.0$, $P = 0.029$], but the r^2 did not differ between *MI* and *AW* [$F_{(1,13)} = 0.1$, $P = 0.798$].

Discussion

This study describes a new experimental protocol for studying and quantifying *MI* of gait in a neuroimaging environment. This protocol allows one to behaviourally distinguish *MI* of gait from *VI*. Furthermore, under these circumstances, we found a tight behavioural correspondence between imagined and actual gait. There were two main findings. First, *MT* increased with increasing path length and decreasing path width in all three tasks. Second, the effect of path width on *MT* was significantly stronger during *MI* and *AW* than during *VI*. The results demonstrate that *MT* is equally sensi-

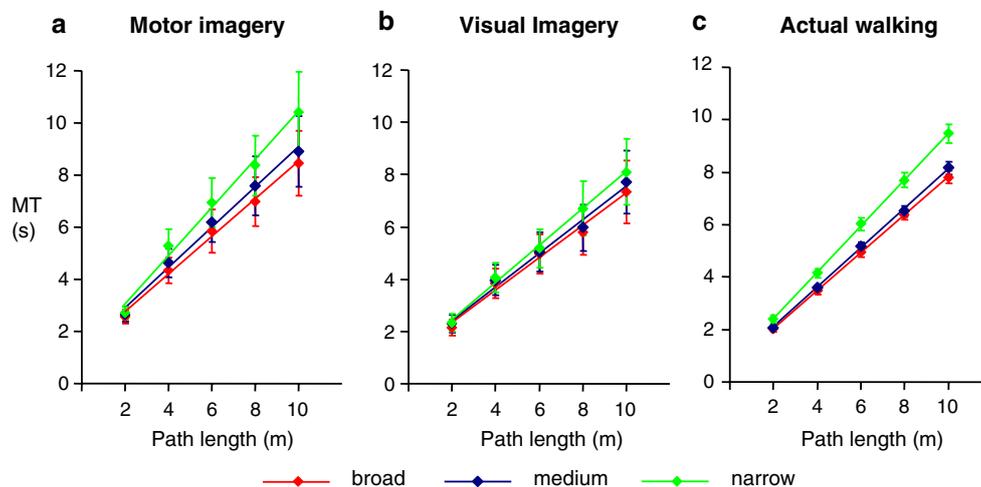


Fig. 3 Movement times (*MTs*) are shown separately for five different path lengths (2, 4, 6, 8, and 10 m) and three different path widths [broad (27 cm), medium (18 cm), and narrow

(9 cm)], for **a** motor imagery (*MI*), **b** visual imagery (*VI*), and **c** actual walking (*AW*). Data represent mean \pm SEM. Lines represent regression curves between *MT* and path length

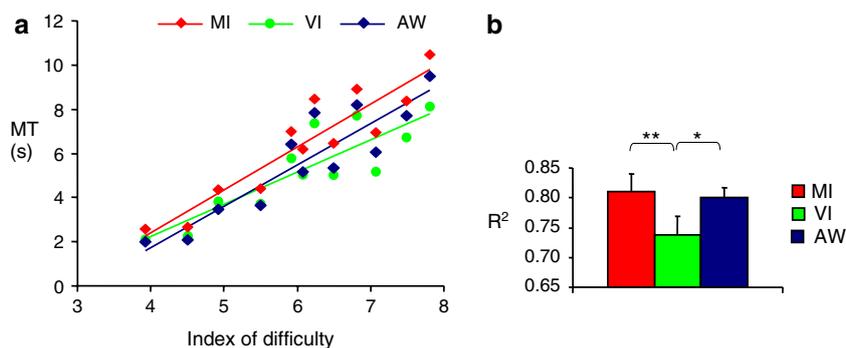


Fig. 4 a Average movement times (*MTs*) plotted against the index of task difficulty (*ID*) for motor imagery (*MI*), visual imagery (*VI*), and actual walking (*AW*). *ID* is calculated for each condition with the following formula: $\log_2(2 \times \text{PATH LENGTH}/$

PATH WIDTH). *Lines* represent regression curves between *MT* and *ID*. **b** Average r^2 of the correlation between *MT* and *ID* for each of the different tasks. * $P < 0.05$, ** $P < 0.01$ (post hoc comparison of r^2 across the different tasks)

tive to path length and path width during both actual and imagined gait performance, suggesting that subjects complied with the *MI* task. The stronger effect of path width during *MI* and *ME* than during *VI* suggests that this protocol allows one to behaviourally distinguish between *MI* and *VI*.

There was a close temporal relationship between actual and imagined walking. This finding suggests that subjects were able to preserve the temporal organization of gait during *MI* of gait, performed in the new setting. This result is not trivial since no previous study has examined the temporal relationship between actual and imagined gait while actual gait is performed in a real environment and imagined gait is performed while sitting on a chair and facing a computer screen presenting photographs of the same environment. Our results demonstrate that the two-dimensional photographs provided sufficient and relevant information about the length and the width of the walking trajectories, and that subjects were able to imagine walking in an environment in which they were not actually present. Another new aspect of this study is that we demonstrated that actual and imagined walking evoked similar *MTs* across a relatively large number of trials. This finding indicates that it is possible to obtain a stable and functionally relevant performance even across multiple trials, a necessary requirement for using this experimental protocol in the context of noisy neurophysiological measurements like *fMRI* or *TMS* that rely on multiple-trial averaging.

In the study of Stevens (2005), imagined walking times were shorter than *AW* times. Here, we found no significant differences in *MTs* between *MI* and *AW*. This discrepancy is likely due to differences in the instructions given to the subjects. Stevens instructed subjects to imagine walking as fast as possible, whereas we asked the subjects to walk at a natural pace. We used these instructions in order to test the validity of

our settings during performance and imagery of gait at a natural speed, and with the further goal of using this setting in neurological populations. More generally, this result illustrates that, during tasks that explicitly require the subjects to engage in mental imagery, task instructions influence the assumptions and beliefs the subjects use to solve the task at hand (Pylyshyn 2002). Other implicit imagery tasks (Johnson-Frey 2004; Parsons 1987, 1994) might be less prone to this effect.

The differential effect of path width during *VI* compared to *MI* and *ME* indicates that this protocol allows one to obtain behavioural indexes to distinguish between *MI* and *VI*. The distinction between *MI* and *VI* was however less pronounced than observed by Stevens (2005). Whereas Stevens found no effect of path width on *MT* during *VI*, we found a trend that *MT* increased with decreasing path width during *VI*. There are several possible explanations for this discrepancy. One possible explanation could be that *MI* experience influenced *VI* in our experiment. In the study by Stevens (2005), *MI* and *VI* were performed by two different groups of subjects, whereas in our experiment all subjects performed both tasks. Therefore *MI* experience might have influenced *VI* performance in our study. However, the order of the *MI* and *VI* task was randomized across subjects, and the effect of path width on *MTs* during *VI* was the same when *VI* preceded or followed *MI*. Differences in task instructions might be a more likely explanation. Stevens instructed subjects to imagine seeing the disc moving “as fast as possible,” and she found that *MTs* were smaller during *VI* than during *MI*. In contrast, we did not specify the speed of the moving disc, in order to avoid overall differences in *MTs* between *MI* and *VI*. We tried to avoid these overall differences since they might be considered a source of confounds in the context of neuroimaging

experiments (Wilkinson and Halligan 2004). However, by not giving subjects any information about the speed of the moving disc, in combination with explicitly instructing subjects to pay attention to the different path widths, some subjects may have reasoned that the disc movement would be influenced by the path width. For example, subjects may have imagined some motoric agent causing the movement of the disc. We tried to prevent this by specifically instructing subjects to imagine seeing the disc moving autonomously. However, we cannot exclude the possibility that some subjects imagined a motoric agent influencing the movement of the disc. In a follow-up imaging study, we have addressed this issue by showing a video of the disc moving autonomously at constant speed through the corridor prior to the experiment. We found this procedure to considerably reduce the effect of path width on MTs in the VI trials (Bakker et al. 2006).

It has been argued that any close temporal relationship between actual and imagined movements might be attributable to tacit knowledge about how long it would take to actually execute the movement (Pylyshyn 2002). While this is an inherent problem of all mental chronometry studies, ongoing work in our lab suggests otherwise, since preliminary analyses of an ongoing fMRI study shows that performance of the MI task evokes specific responses within the motor system (Bakker et al. 2006).

This study was designed to evoke first-person kinaesthetic imagery (Jeannerod 1994). For instance, subjects were shown photographs of walking environments that were taken from a first-person perspective. Furthermore, we exploited the fact that walking along a narrow path requires more voluntary control than walking along a broad path. Accordingly, the path width manipulation directed subjects' attention towards their own movements as they imagined walking along each of the different paths. Subjects were also explicitly instructed to imagine walking along the paths in a first-person perspective, and to imagine as if their own legs were moving. Crucially, in a previous related study (Stevens 2005) it was clearly shown that, under these conditions, subjects' body posture influenced performance of the MI task, but not of the VI task. This provides strong evidence for the presence of first-person kinaesthetic imagery. Therefore, although we do not directly address this issue in this experiment, we believe that the task settings, the explicit instructions, and the previous evidence make it likely that subjects used first-person kinaesthetic imagery during performance of the MI task.

Conclusions

We have provided a replication of the behavioural finding described in Stevens (2005), showing that MI of gait is sensitive to the same temporal and spatial constraints as AW movements. We have shown that under circumstances that are suitable for a neuroimaging setting it is possible to obtain behavioural indexes that distinguish between MI and VI, and that show the high temporal correspondence between actual and imagined gait. These results open the possibility of using this protocol to explore the neurophysiological correlates of gait control in healthy subjects, and in neurological populations with gait disturbances related to cerebral pathologies, for example, in patients with Parkinson's disease.

Acknowledgments This research was supported by the International Parkinson Fonds (to MB and BB). FPdL and IT were supported by the Dutch Science Foundation (NWO: VIDI grant no. 452-03-339).

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