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RESEARCH ARTICLE

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Eyes wide shut: How visual cues affect brain patterns of simulated gait

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Abstract

In the last 20 years, motor imagery (MI) has been extensively used to train motor abilities in sport and in rehabilitation. However, MI procedures are not all alike as much as their potential beneficiaries. Here we assessed whether the addition of visual cues could make MI performance more comparable with explicit motor performance in gait tasks. With fMRI we also explored the neural correlates of these experimental manipulations. We did this in elderly subjects who are known to rely less on kinesthetic information while favoring visual strategies during motor performance. Contrary to expectations, we found that the temporal coupling between execution and imagery times, an index of the quality of MI, was less precise when participants were allowed to visually explore the environment. While the brain activation patterns of the gait motor circuits were very similar in both an open-eyed and eye-shut virtual walking MI task, these differed for a vast temporo-occipito-parietal additional activation for open-eyed MI. Crucially, the higher was the activity in this posterior network, the less accurate was the MI performance with eyes open at a clinical test of gait. We conclude that both visually-cued and internally-cued MI are associated with the neurofunctional activation of a gait specific motor system. The less precise behavioral coupling between imagined and executed gait while keeping eyes open may be attributed to the processing load implied in visual monitoring and scanning of the environment. The implications of these observations for rehabilitation of gait with MI are discussed.

KEYWORDS
fMRI, gait, motor imagery, motor rehabilitation, visual cues

1 | INTRODUCTION

The decay of gait-related skills is one of the defining traits of aging. The ensuing high prevalence of accidental falls is one major cause of disability, with great individual sufferings, reduced life expectancy and

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considerable costs for the society for hospitalization and rehabilitation (Alexander, 1996; Gillespie et al., 2012). This is why establishing which preventive or rehabilitative interventions are the most effective in preserving or restoring gait abilities in older people has primary importance.

Motor imagery (MI) is one of the tools that one could use for addressing this issue. MI is a mental state in which real movements are internally evoked without any overt action (Jeannerod & Frak, 1999; Munzert & Zentgraf, 2009). MI seems not readily available from birth (Conson, Mazzarella, & Trojano, 2013; Piedimonte, Garbarini, Rabuffetti, Pia, & Berti, 2014): MI abilities mature late in childhood and they are available until later in life (Saimpont, Malouin, Tousignant, & Jackson, 2013), even though elderly subjects present some qualitative differences in the way they access motor representations through imagination (Mulder, Hochstenbach, van Heuvelen, & den Otter, 2007).

Worth of note, MI has not only common temporal features ("isochrony" Decety, Jeannerod, & Prablanc, 1989), but also similar anatomo-functional correlates with actual motor execution (ME) of any given act (Hétu et al., 2013).

Taken together, this evidence justifies the use of MI in training and rehabilitating motor control. MI may be particularly useful in treating conditions where practical limitations, such as postsurgery immobilization or reduced physical strength, limit the applicability of direct physical training (see for example Gandola et al., 2017; Gandola et al., 2019; Zapparoli et al., 2020). Although the beneficial effect of MI practice has been already shown in both normal and pathological populations (Braun, Beurskens, Borm, Schack, & Wade, 2006; Lotze, Scheler, Tan, Braun, & Birbaumer, 2003), to date very little attention has been paid to how MI should be triggered to achieve the best possible results. One size fits all? Not all forms of motor imagery are alike nor their potential beneficiaries.

MI can be evoked implicitly, for example, by asking subjects to make perceptual judgments, like in the hand laterality task (Parsons, 1987), or explicitly, when subjects are instructed to mentally rehearse gestures or complex behaviors like, for example, the movements implied by walking. Having decided that one prefers one form of imagination, let us say the explicit form, other variables may become important to consider. One of these is whether the eyes should be kept shut or open. In the second case, a wealth of visual information is added to mental activity of motor rehearsal making perhaps the motor imagery activity closer to real-life experience (Liu, Chan, Lee, & Hui-Chan, 2004; Rodionov, Zislin, & Elidan, 2004; Stevens & Stoykov, 2003).

Would the additional visual information help? It is well known that providing external cues has a beneficial effect on motor skills recovery (Liu et al., 2004; Verschueren, Swinnen, Dom, & De Weerdt, 1997). Verschueren and colleagues (Verschueren et al., 1997) showed that delivering visual cues enhances the performance of a motor coordination task in a group of Parkinson's disease patients. Moreover, the beneficial effect of visually-cued training has also proved to reduce the occurrence of falls in frail older people (Sihvonen, Sipilä, Taskinen, & Era, 2004) and to improve postural control (Pinsault & Vuillerme, 2008).

Heremans et al. (2009) examined the potential differences in MI quality, rather than ME, during visually- and internally-cued MI tasks performed by young participants: they found more accurate coupling between eye movements recorded during imagery with eyes open and eye movements recorded during actual movement execution. Moreover, they reported higher self-report imagery vividness scores in the eyes open form of MI. They concluded that open-eyed MI may give some advantage (Heremans et al., 2009).

To summarize, all the aforementioned evidence seems to support the idea that explicit motor imagery should be performed with the eyes open when used for rehabilitation.

However, a deeper look into the literature may suggest some caution before drawing definitive conclusions on this matter, particularly if one considers that not all age-ranges nor all motor behaviors are necessarily alike.

For example, younger and older people are not entirely comparable when it comes to motor imagery and motor control. Behavioral evidence has shown a lower reliance on kinesthetic features in favor of visual strategies in older subjects (Malouin, Richards, & Durand, 2010). Moreover, age-related differences have been reported in the neurofunctional networks of motor imagery: besides a significant overlap in motor-imagery-related activation patterns between young and older subjects (Zapparoli et al., 2013), the latter show hyperactivations of posterior networks during eyes-shut explicit motor imagery (see for example also Allali et al., 2014). Nedelko et al. (2010) also reported the same greater activation patterns in occipital and parietal cortices for older subjects. These differences have been interpreted according to a compensatory hypothesis (Reuter-Lorenz & Cappell, 2008), which posits that age-related over-activations in older adults may represent the effort to maintain their behavioral performance at a juvenile-like level, successful, in compensation, or unsuccessful, in compensatory attempts. In this case, the posterior cortices might be particularly relevant in older adults to cope with age-related changes in the quality of motor imagery, who may rely on additional visual strategies during motor imagery tasks (Malouin et al., 2010; Zapparoli et al., 2013; Zapparoli et al., 2016). Giving this evidence, one could hypothesize that adding visual cues during motor imagery may ease the access to mental motor representations in older subjects optimizing task performance.

However, as said, the visual cortices are already more engaged during eyes-shut motor imagery in elderly people. If this over-activation has a functional meaning—it has been proved to correlate with the worsening of the MI performance in elderly subjects (Zapparoli et al., 2013)—another possibility arises, namely that the incoming visual information may interfere with MI processes.

In particular, the elaboration of additional cues to those evoked with motor imagery may become too demanding, with a consequent worsening of performance in the primary task of retrieving kinesthetic motor sensations. This would be in line with suggestion that aging is characterized by a reduction of available resources (Cabeza, 2002), at least in the motor domain. No such hypotheses have been tested so far, particularly with regard to gait behaviors and by using a combination of clinically relevant behavioral and functional imaging tasks.

1.1 | Aims of the study

In the present study, the fourth of a series of investigations on the neural representations of gait along the adult life-cycle in healthy and pathological populations (Sacheli et al., 2017, 2018, 2020), we investigated the behavioral and neurofunctional effects of visual-cues on motor imagery of gait.

We aimed to provide a neuro-functionally informed rationale for the adoption of appropriate imagery techniques to complement rehabilitation practices and prevent the decay of gait-related skills in older adults or to boost rehabilitation in neurological or orthopedic patients.

To this end, we compared behavioral measures and brain correlates of motor imagery of gait across different conditions by manipulating the presence/absence of visual cues. At a behavioral level, we tested these effects in two independent samples (Experiment 1 and Experiment 2) by using the popular clinical task known as Timed Up & Go task performed in its actual or imagined form (TUG, Podsiadlo & Richardson, 1991). To assess the impact of visual cues on brain activation patterns for motor imagery, in Experiment 2 we also used the same fMRI *virtual walking* paradigm that was described in our previous publications (Sacheli et al., 2017, Sacheli et al., 2018, Sacheli et al., 2020). With the fMRI data, we planned to test the impact of visual information on the neural correlates of the virtual walking tasks. We also planned to test the presence of correlations between the fMRI data and the behavioral data at the imagined TUG (iTUG).

We had specific predictions in mind at the behavioral and functional anatomical level, in line with two possible alternative scenarios.

According to scenario A, open-eyed MI may permit a better coupling between the time taken to imagine an act (the stroll required by the TUG) and its execution. At the functional anatomical level, this would translate in the modulation of the brain activity of regions responsible for gait motor control depending on the amount of visual information available. Specifically, one may expect the activity of brain regions of interface between motor circuits for gait and visual monitoring to correlate positively with a better MI performance at the clinical task of gait.

According to a second scenario B, open-eyed motor imagery may rather be associated with less precise coupling with motor execution due to a competition within the same neural circuitry. In other words, the incoming visual information may interfere with the recruitment of compensatory visual strategies, thus worsening performance. At the functional anatomical level, this would be reflected by the lack of interaction between the eyes open condition and the main patterns of activity of the gait control circuits. In principle, one could also anticipate a negative correlation of the brain activation patterns with the eyes open motor imagery performance at a clinical task of gait.

Admittedly, at the outset of our study, we rooted for scenario A. However, whatever the outcome of our experiments, what counts here is that our experimental design allowed us to test the opposites outcomes of the two scenarios, without being biased by our initial expectations, as we describe next. As a last note, we anticipate that our fMRI task also allowed us to test whether the presence of visual cues has a different effect depending on the specific imagery task: in the present study, as we did in some of our previous studies Sacheli et al., 2020; Sacheli et al., 2018; Sacheli et al., 2017, we compared simple motor imagery with a condition that combines motor imagery with body movements (Dynamic Motor Imagery, Fusco et al., 2016; Fusco et al., 2019; Fusco et al., 2014; Guillot, Moschberger, & Collet, 2013; Kanthack et al., 2016).

2 | EXPERIMENT 1

To explore the effect of providing visual cues on the abilities of the older people to form gait motor representations, we first performed a purely behavioral study on a first sample of participants. They underwent a modified version of Timed Up & Go task (TUG, Podsiadlo & Richardson, 1991) whereby, after an explicit performance of the motor task with actual walking, the same task was performed in an imaginary form either while keeping the eyes shut or while keeping the eyes open. Moreover, in order to understand whether any condition-specific advantage could be explicitly perceived, participants were asked to rate the goodness of their imagination using visual analogue scales (VAS). This was done in line with other studies addressing the subjective vividness of MI in different conditions (see for example, Hasegawa et al., 2017; Lotze et al., 2003). We chose this approach since the available validated scales for MI vividness assessment (e.g., VMIQ, Isaac, Marks, & Russell, 1986) measure individuals' ability to imagine themselves performing simple motor tasks (e.g., walking, running, kicking a stone…) from different perspectives (e.g., first or third person perspectives). In our study, we were particularly interested in addressing the vividness of MI during the specific execution of the Timed Up and Go Test in the two imaginary forms proposed here.

2.1 | Materials and methods

2.1.1 | Participants

Twenty-nine healthy older participants (17 males, age: 70.7 ± 5.9 years; education: 10.5 ± 3.8 years) took part in the study. None of the participants reported any current or previous motor disorder or any history of neurologic or psychiatric disease. All subjects were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971).

A short neuropsychological screening, including the Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975), the Raven's Colored Progressive Matrices (Raven, Raven, & Court, 1998) and the Digit Span Memory Test (Novelli, Papagno, Capitani, & Laiacona, 1986), was performed by each participant. See Table S1a.

The experimental protocol was approved by the Local Ethics Committee (Comitato Etico Ospedale San Raffaele; prot. L3020) and carried out in accordance with the ethical standards of the 1964 Declaration of Helsinki and later amendments. All participants provided written informed consent to take part in the study.

A schematic summary of our experimental design can be found in Figure 1a and Table S2.

2.1.2 | Behavioral task and data analysis

In order to assess the quality of gait motor representations across a visually-cued MI condition and a internally-cued MI condition, all participants performed a modified version of the TUG (Podsiadlo & Richardson, 1991), adapted from Beauchet et al. (2010). There were three different experimental conditions. In the motor execution (ME) condition, subjects were seated and instructed to walk 3 m, turn around a landmark, walk back to the chair and sit down saying "stop". In the MI condition without visual cues (iTUG VC-), subjects sat in the chair and were instructed to imagine performing the TUG while keeping their eyes closed and to say "stop" when they were done. In the MI condition with visual cues (iTUG VC+), participants underwent the same imagery task of the previous condition, but they were allowed to keep their eyes open and to see the path while they were imaging to walk. Times for each condition were recorded with a stopwatch to the nearest 0.01 s. The stopwatch was started on the command "ready–set–go" and stopped as the subject sat down and said "stop." Participants performed the task twice and we averaged the times of the two trials (see Figure 1a). While the ME condition was always executed first, the order of the iTUG VC- and VC+ iTUG conditions was counterbalanced across subjects: the first recruited subject performed the ME condition, then the iTUG VC+ and finally the iTUG VC-, the second one also performed the ME condition first and then the two imagery tasks in the reversed order, the third participant followed the same order as the first one, and so on.

We assessed the mental chronometry abilities (CA) by calculating the time discrepancy between the actual motor execution condition and motor imagery, separately for the two different mental imagery modalities (VC- and VC+), with the following formula (Allali et al., 2014): CA = (ME − MI)/[(ME + MI)/2].

The lower the CA score, the smaller the difference between times recorded during the motor execution condition and the motor imagery, which would index better isochrony and higher motor imagery abilities.

Such coupling is considered an index of the quality of MI (Allali et al., 2014), since a good MI performance is qualified by its similarity with the time needed to perform the same movement.

After the execution of (each version of) the iTUG, participants were asked to rate the vividness of their imagination (self-report quality of imagery) using visual analogue scales (VAS). Subjects marked a location on a 100-mm vertical line according to their assessment of vividness. The two extremes of the line indicated judgments of MI vividness corresponding to "Not clear at all" or "Very clear".

We then compared CA values and the self-report quality of imagery analyses (VAS) of VC- and VC+ conditions. This was done by

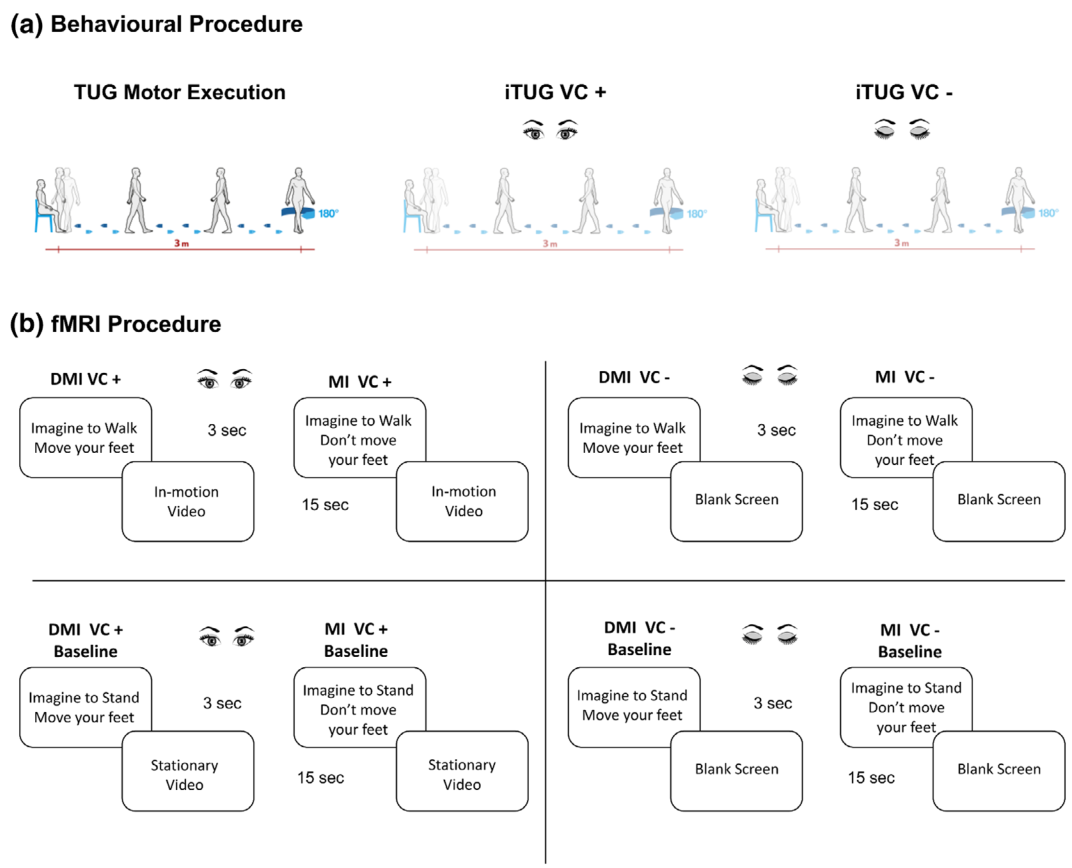

FIGURE 1 Graphical illustration of the (a) behavioral and (b) fMRI procedure that we applied in Experiment 1 (a) and Experiment 2 (a+b)

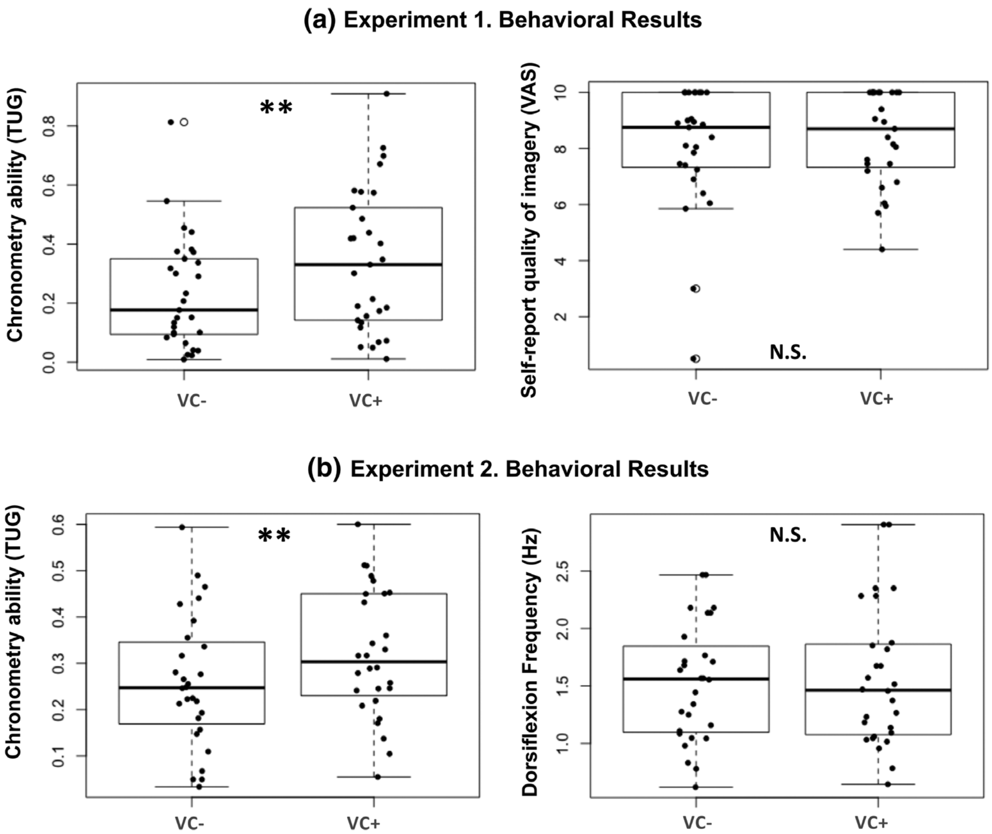

FIGURE 2 (a) Behavioral results for the Experiment 1. Left Panel. iTUG task performance with (VC+) and without (VC-) visual cues, measured by means of the chronometry abilities index (CA). Right Panel. Self-report quality of imagery in the iTUG task with (VC+) and without (VC-) visual cues, measured by means of Visual Analogue Scales (VAS). (b) Behavioral results for the Experiment 2. Left Panel. iTUG task performance with (VC+) and without (VC-) visual cues, measured by means of the chronometry abilities index (CA). Right Panel. Ankle-dorsiflexion movements frequency recorded during the fMRI virtual walking task, performed with (VC+) and without (VC-) visual cues

means of nonparametric paired *t*-test (Wilcoxon signed-rank test), since both the CA data and the VAS data were not normally distributed, according to Shapiro–Wilk test (test's *p*-values <.05).

2.2 | Results

2.2.1 | Behavioral results: Mental chronometry abilities and subjective ratings on imagination quality

The Wilcoxon signed-rank test on CA data showed a significant difference between the VC- and the VC+ conditions (Z = 320, *p* = .008, Cohen's *d* = 0.56). The median CA rank of the VC- condition was significantly lower (median CA = 0.180; interquartile range = 0.38) as compared with the VC+ condition (median CA = 0.33; interquartile range = 0.26). See Figure 2a, left panel, and Table 1, first row.

No differences were found between the VC- and the VC+ conditions in the self-report quality of imagery data (median VAS VC- = 8.75, interquartile range = 2.67; median VAS VC + =8.70, interquartile range = 2.67; Z = 137, *p* = .745, Cohen's *d* = 0.15). See Figure 2a, right panel.

To gain more explicit evidence for the lack of a difference in in the self-report quality of imagery data between the VC+ and VC- conditions, we applied a Bayesian approach. The data provide moderate evidence (BF10 = 0.12) in favor of the null hypothesis (i.e., absence of a difference in self-report quality of imagery data between the VC+ and VC- conditions). This last analysis allows us to infer that the observations are likely to be reproducible, since even the comparisons that did not showed a significant difference between them had enough statistical power.

TABLE 1 Behavioral performance for Experiment 1 and Experiment 2: group motor execution (ME) and imagination (MI) times for the Timed Up and Go without (VC-) or with (VC+) visual cues (mean±standard deviation).

	ME	iTUG VC–	iTUG VC+
Experiment 1	8.94 (±1.60) s	7.49 (±2.14) s	6.51 (±1.99) s
Experiment 2	8.81 (±1.32) s	6.89 (±1.37) s	6.49 (±1.44) s

3 | EXPERIMENT 2

To further explore these findings, we rerun the same behavioral experiment in a new sample of subjects, in which we also evaluated the functional anatomical correlates of motor imagery for gait performed either with eyes open or with eyes shut.

3.1 | Materials and methods

3.1.1 | Participants

Twenty-eight healthy older participants (13 males, age 64.8 ± 5.3; education 15.3 ± 3.3 years) were included in this second study. None of the participants reported any current or previous motor hindrance or any history of neurologic or psychiatric disease. All subjects were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). See Table S1b.

Comparison of demographic and neuropsychological characteristics of the two samples of subjects. There was no difference in the M/F ratio (Exp1 = 17 M/12 F; Exp2 = 13 M/15F; Chi-square[1] = 0.85; $p = 1$). The first sample was made of subjects, on average, 5 years older (Mean Exp1 = 70.7 (5.9); Mean Exp2 = 64.8 (5.3); Student's t (55) = 3.97; $p < .001$) and with better educational level (Median Exp1 = 11 (3.79); Median Exp2 = 16 (3.32); Mann–Whitney U = 154; $p < .001$). These demographic differences, however, were not associated with sizeable differences in terms of cognitive functioning on neuropsychological testing: general cognitive functioning (MMSE, median Exp1 = 30 (1.43); median Exp2 = 28.5 (1.28); Mann–Whitney U = 280; $p = .266$); short-term memory (Digit forward, mean Exp1 = 5.81 (0.76); mean Exp2 = 6.46 (1.24); Student's t(55) = −2.76; $p = .056$); working memory (Digit backward, mean Exp1 = 4.07 (1.07); mean Exp2 = 4.92 (1.25); Student's t(55) = 2.42; $p = .133$) and abstract reasoning (Raven's Matrices, median Exp1 = 32 (4.22); median Exp2 = 34.5 (3.12); Mann–Whitney U = 288; $p = .42$). See Table S1c.

The experimental protocol was approved by the Local Ethics Committee (Comitato Etico Ospedale San Raffaele, prot. L3020) and was carried out in accordance with the ethical standards of the 1964 Declaration of Helsinki and later amendments. All participants provided written informed consent to take part in the study and had no contraindication to MRI.

The experimental procedure included the TUG, the iTUG VC+ and the iTUG VC- tasks performed outside the scanner and a "virtual walking" task executed during fMRI. Here, both the behavioral and neurofunctional MI tasks were performed in two versions: one visually-triggered, the other internally-cued (see below).

3.1.2 | Behavioral task and data analysis

The procedure of the behavioral task (TUG and iTUG tasks, performed with open and closed eyes, VC+ and VC-) was identical to the one described for Experiment 1.

To test differences in CA between the iTUG VC+ and VC- conditions, we performed a paired samples t-test since data were normally distributed, according to Shapiro–Wilk test (test's p-values >.65).

Moreover, we calculated the correlation coefficient between the CA of the two conditions.

3.1.3 | fMRI task

The gait imagery tasks performed in the MRI scanner were adapted from Sacheli et al. (2017, 2018, 2020).

The task required participants to perform MI of walking in two different conditions. In the pure MI condition (MI), subjects were instructed to imagine walking along a path (see below for further details) while having their foot at rest. In the Dynamic Motor Imagery condition (DMI), subjects were instructed to imagine walking along the same path, and to combine this imagery task with the execution of overt ankle-flexion movements mimicking gait behavior, and performed in pace with the imagined walking rhythm (see for example, Guillot et al., 2013).

As for the behavioral task, also during fMRI scanning subjects underwent two different versions of this virtual walking task. In the task with visual cues (VC+), gait imagery was aided by in-motion visual stimuli of a path in a park shown in the first-person perspective. In the task with no visual cues (VC-), participants were required to imagine walking while keeping their eyes closed. For both tasks, as a baseline condition, participants were required to imagine "standing on the spot", and in the VC+ task, stationary movies were shown. VC+ and VC- tasks were presented in different fMRI runs and in counterbalanced order across subjects. Before starting the fMRI session, the participants practiced the task outside the MRI scanner for about 10 min, so that they could familiarize with the videos and learn to correctly execute ankle dorsiflexion when prompted. They were asked to imagine walking in a similar scenario in both VC+ and VC- conditions (see Figure 1b).

We included three factors in our experimental design: "Visual Cues" (VC+/VC-), "Foot Movements (M+/M-) and "Imagery" (Walk/Stand).

In a first full factorial design we measured, as a control analysis, the differences in the neural correlates of foot movement execution during both VC+ and VC- motor imagery.

In a second full-factorial design, we examined differences in brain activations during gait imagery with or without foot movements (as compared to imagery of standing still) and modulation thereof introduced by the presence of visual cues.

Stimuli and procedure

During the VC- task, participants were asked to imagine standing or walking along an imagined path, following visual instructions depicted on the screen. In the "virtual walking" condition (Walk), they were instructed to imagine walking along a path. In the baseline standing condition (Stand) they were instructed to imagine standing on the spot. At the beginning of each trial, a written prompt (3 s) indicated the motor imagery condition (Walk or Stand). Participants were instructed to close their eyes and perform the task for 15 s, until they heard the auditory instruction "stop". The written prompt also indicated the motor execution condition (Move or No-move). In the "move your feet" condition (DMI), 50% of the trials, the participants executed alternated ankle dorsiflexion (Dobkin, Firestine, West, Saremi, & Woods, 2004) in-step with the rhythm that they imagined in the Walk condition. As a proxy of actual walking patterns, we employed ankle dorsiflexion because it is applicable to the fMRI environment, and its neural underpinnings proved to correlate with actual walking performance (Dobkin et al., 2004). In the No-move condition (pure MI), the foot movements were not requested and participants were told that a daily life analogue of the task would have been stepping on the spot. Therefore, four conditions were presented:

imagine walking combined with foot movements, imagine standing combined with foot movements, imagine walking without foot movements, imagine standing without foot movements.

In the VC+ task, similarly to the VC- task, participants were required to imagine walking or standing on the spot. However, here visual cues illustrating the to-be-imagined scenario were provided. The cues consisted of 15 s naturalistic videos of a path leading through a park in two conditions: in-motion, "virtual walking" condition (Walk), or stationary, standing condition (Stand) that served as baseline. Throughout the experiment, participants were asked to imagine standing (Stand) or walking along the path (Walk) as if the camera were "their own eyes" (Iseki, Hanakawa, Shinozaki, Nankaku, & Fukuyama, 2008). In the Walk condition, the scene moved forward at a speed compatible with slow human walking rhythm (≈ 1.1 m/s). Similar to the VC- task, at the beginning of each trial, a written prompt (3 s) indicated both the motor imagery condition (Walk or Stand). The written prompt also indicated the motor execution condition (Move or No-move).

Therefore, the VC+ task was characterized by the same experimental conditions as in the VC– one: imagine walking combined with foot movements, imagine standing combined with foot movements, imagine walking without foot movements, imagine standing without foot movements.

For both tasks, the experimenter monitored the participants' foot movements during the entire session to ensure they followed the instructions. Eight times per run (one per video type), the participants were asked whether they had imagined the movement or not. The purpose of these attention-getter questions was to keep participants focused on the task. None of the participants failed to follow the instructions; moreover, they reported to have correctly performed the imagery task in the majority of the investigated trials for both the VC+ (98.96 ± 0.04% of trials) and the VC- tasks (97.28 ± 0.06% of trials).

Each task lasted 11.5 min and 230 scans were acquired. The first 10 scans, corresponding to the visualization of task instructions, were discarded from the analysis. Each run included 32 "trials" of 15 s videos (VC+ condition) or 15 s black screens (VC- condition), that is, eight trials per experimental condition (i.e., Walk-MI, Stand-MI, Walk-DMI, Stand-DMI), for a total of 40 scans acquired per experimental condition.

A semicircular cushion supporting the legs was provided so that the participants could freely move their ankles without bending their knees.

Stimuli presentation was controlled by Cogent 2000 MATLAB Toolbox (MathWorks). Visual stimuli were delivered using VisuaStim fiber-optic goggles (600×800 pixel resolution). Responses were recorded through a response box placed under the participant's right hand (Resonance Technology Inc., Northridge, CA). Subjects' ankle-dorsiflexion movements were video-recorded (by a camera placed outside the scanner room), in order to calculate the movement frequency and to compare it across different conditions.

fMRI data acquisition

MRI scans were acquired using a Siemens Magnetom Avanto 1.5 T scanner (Siemens AG, Erlangen, Germany), equipped with gradient-echo echoplanar imaging. Two hundred and thirty functional volumes were acquired for each task (flip angle 90°, TE 60 ms, TR 3000 ms, FOV phase 250, matrix 64×64, 31 slices, slice thickness 4 mm, interleaved acquisition). A MPRAGE high-resolution T1-weighted structural image was also acquired for each subject (flip angle 35°, TE 5 ms, TR 21 ms, FOV 256×192 mm^2, matrix 256×256, TI 768, for a total of 160 axial slices with $1 \times 1 \times 1$ mm^3 voxels).

Preprocessing

Raw functional data were reconstructed and converted from the DICOM to the NIfTI format using the MRIcron software (www.mccauslandcenter.sc.edu/crnl/mricron/). The subsequent image manipulations and statistical analyses were performed in the MATLAB platform (2016b, Math Works, Natick, MA) with the Statistical Parametric Mapping software package (SPM12 - Wellcome Department of Imaging Neuroscience, London, UK). Functional images were first realigned to the first acquired volume and unwarped to minimize the effect of the subjects' movement during the session. The high-resolution T1-weighted structural image of each participant was segmented and normalized to the MNI (Montreal Neurological Institute) stereotactic space to allow between-subject comparison (Ashburner & Friston, 2005), and it was then co-registered to the realigned and unwarped functional volumes. The functional images were then normalized by applying the Deformation Fields employed during the segmentation of the structural data and the data matrix was interpolated to produce voxels $2 \times 2 \times 2$ mm in dimension. The normalized scans were finally smoothed using a gaussian filter with 10x10x10mm as full width at half-maximum (FWHM) value, to improve the signal-to-noise ratio in the data.

An additional step was included in order to reduce the impact of movement artifacts by using the ARtifact detection Tools (ART, Withfield-Gabrieli, https://www.nitrc.org/projects/artifact_detect/). This toolbox allows identifying and discarding from the analyses the scans that could lead to artifactual statistical effects due to excessive movement. Thresholds were set at 1 mm scan-to-scan head movement and 3 standard deviations of scan-to-scan global signal intensity change. Experimental subjects that exhibited more than 20% outlier scans in the whole experimental run would have been excluded from the subsequent statistical analyses. No participant exceeded these thresholds.

Statistical analysis

Preprocessed functional volumes were entered in a two-level statistical analysis procedure based on the General Linear Model. This allowed testing for statistical differences in the blood-oxygen-level dependent (BOLD) signal within the different experimental conditions. The signal was analyzed by a convolution with a canonical hemodynamic response function (Worsley & Friston, 1995). The time series was high-pass filtered at 128 s to remove artifactual contributions to the fMRI signal such as noise from cardiac and respiratory cycles. Each of the 15 s time period during which the participants performed the gait imagination task represented a single trial in a block design, identified by its specific onset and a fixed duration of 15 s.

We included three factors in our experimental design: "Visual Cues" (VC+/VC-), "Foot Movements (M+/M-) and "Imagery" (Walk/Stand). At the first level, two separate within-subjects fixed-effect analysis allowed the condition-specific effects to be estimated, separately for the two tasks (VC– and VC+). In particular, each of the following conditions corresponded to a specific regressor: Stand(M-), Walk(M-), Stand(M+), Walk(M+). Moreover, specific regressors of no interest were defined for the written prompts (lasting 3 s each) and the attention-getter questions regarding the goodness of the imagination (lasting 8 s each). Realignment parameters from the preprocessing steps of the analysis were also included in the GLM, as well as specific regressors generated by the ART toolbox to exclude the outlier scans that exceeded the movement thresholds. The Wilcoxon signed-rank test on the excluded scan data did not show a significant difference between the VC- and the VC+ conditions (Z = 131, p = .396, Cohen's d = –2.05. VC- median = 5, interquartile range = 7; VC+ median = 7 interquartile range = 6).

At the second level of analysis, two orthogonal 2×2 ANOVAs were employed. First, we measured differences and similarities across the VC- and VC+ in the cortical activations associated with actual foot movements (Foot Movement analysis).

We then evaluated differences and similarities in the activation patterns of activations associated with motor imagery across the different VC- and VC+ tasks, also with reference to possible different patterns associated to both MI and DMI (*Virtual Walking analysis*). A graphical summary of our fMRI analyses can be found in Figure S1.

Foot movement analysis. As a control analysis to identify the motor network involved in foot movement control, we first mapped differences in the motor network responsible for foot movement execution across the two different VC- and VC+ tasks. At the first-level of statistical analysis (single-subject level), we calculated the following linear contrasts:

1. Walk(M+) > Walk(M-) in the VC+ run
2. Stand(M+) > Stand(M-) in the VC+ run
3. Walk(M+) > Walk(M-) in the VC- run
4. Stand(M+) > Stand(M-) in the VC- run

These contrasts convey information on the cortical activations recorded during explicit foot movement execution during the stand and the walk condition, where the implicit motor component of the imagery task is subtracted out by the baselines.

These contrast images were entered into a 2x2 factorial ANOVA, with "Visual Cues" (VC- vs. VC+) and the "Imaginative Task" (Walk vs. Stand) as within-subject factors. This analysis allows the (i) mapping the overall main effect of Foot Movements (linear contrast: 1 1 1 1) to identify the brain regions associated with the execution of lower limb movements compatible with gait behaviors (i.e., ankle dorsiflexion, see Dobkin et al., 2004), (ii) evaluating differences in the neural correlates of foot movement execution during the VC- and VC+ imagery condition and (iii) considering possible interaction effects between the two factors.

Virtual Walking analysis. We investigated the differences in the neural correlates of motor imagery of gait in the VC- and VC+ tasks, by comparing the brain responses during the in-motion imagery condition (Walk) with those collected while the participants imagined standing on the spot (Stand condition, that served as baseline), and by separately analyzing the trials where explicit ankle dorsiflexion was present (DMI condition) or absent (MI condition). The group-analysis was thus based on the following linear contrasts (calculated at the single-subject level):

1. Walk(M+) > Stand(M+) in the VC+ run → Dynamic Motor Imagery Condition (VC+)
2. Walk(M-) > Stand(M-) in the VC+ run → Motor Imagery Condition (VC+)
3. Walk(M+) > Stand(M+) in the VC- run → Dynamic Motor Imagery Condition (VC-)
4. Walk(M-) > Stand(M-) in the VC- run → Motor Imagery Condition (VC-)

Both the MI and DMI contrasts are associated with the implicit motor component of the imaginative task. However, in the "Walk(M+) > Stand(M+)" contrasts the explicit motor component (linked to the overt movement execution) is canceled out by the subtraction between two conditions (Walk(M-) and Stand(M-)), both associated with overt foot movements, while the implicit motor component of the imaginative task is preserved. This explicit motor component was assessed in the previous Foot movement analysis.

These contrast images were entered into a 2x2 factorial ANOVA, with Visual Cues (VC- vs. VC+) and the Imagery-type (MI vs. DMI) as a within-subject factors. This allowed us to evaluate (i) the general differences in brain activations between gait imagery across VC- and VC + (main effect of "Visual Cues"), (ii) the general differences in brain activations between MI and DMI (main effect of "Imagery-type"), and (iii) whether differences in the way MI and DMI are dealt with across the two different tasks (interaction effect).

All results are reported using the nested-taxonomy strategy recommended by Friston and colleagues (Friston, Holmes, Poline, Price, & Frith, 1996), that is, reporting regional effects meeting either a cluster-wise or voxel-wise family-wise error rate (FWER) correction for multiple comparisons. The cluster-wise correction was applied to data having applied a $10 \times 10 \times 10$ Gaussian smoothing and at $p < .001_{uncorr}$ at the voxel-level, as recommended by (Flandin & Friston, 2017).

3.2 | Results

3.2.1 | Behavioral results: Mental chronometry abilities

The paired-samples t-test on the CA data showed a significant difference between the VC- and the VC+ conditions (t[27] = –4.27, p < .001, Cohen's d = 0.81). The mean CA of the VC- condition was significantly lower (CA = 0.260 ± 0.142) as compared with the VC+ condition (CA = 0.320 ± 0.138). This indicates a tighter matching of the execution times of the TUG task with its imagined version with eyes shut (See Figure 2b, left panel, and Table 1, second row).

3.2.2 | Behavioral results: Ankle dorsiflexion movements

Independent sample tests showed no significant difference between the two conditions (VC+ and VC-) in terms of ankle-flexion frequencies ($t(27) = 1.18$, $p = .25$, Cohen's $d = -0.22$; mean frequency VC-: 1.52 +/– 0.51 movements per second [mov/s]; mean frequency VC+: 1.56 +/– 0.61 mov/s).

To gain more explicit evidence for the lack of a difference in ankle-dorsiflexion movements between the VC+ and VC- conditions, we applied a Bayesian approach. The data provide moderate/strong evidence (BF10 = 0.10) in favor of the null hypothesis (i.e., absence of a difference in ankle-dorsiflexion movements between the VC+ and VC- conditions). This analysis allows us to infer that the observations are likely to be reproducible, since even the comparisons that did not showed a significant difference between them had enough statistical power. See Figure 2b, right panel.

3.2.3 | fMRI results: Foot movements analysis

Main effect of foot movement (contrast 1 1 1 1)

The execution of foot movements was associated with the activation of motor and premotor areas on the median wall, including the precentral gyrus and the paracentral lobule bilaterally, the right SMA and the right postcentral gyrus. Moreover, the foot movement network included brain areas outside the medial wall of the frontal lobe, such as the cerebellum bilaterally, the left supramarginal gyrus, and subcortical regions such as the thalamus bilaterally and the left caudate, putamen and hippocampus. See Table S3 and Figure S2.

Cues-related difference in foot movement execution

The analysis revealed no significant main effect of cues in either direction.

Interaction effect

The ANOVA showed no significant interaction effect Cues × Imaginative Task.

3.2.4 | fMRI results: Virtual walking analysis

Main effect of imagery-type

A wide brain network including the bilateral supplementary motor area and the cerebellum, and the right precentral gyrus, the left parietal operculum and the left supramarginal gyrus showed a main effect of Imagery-type, being more active in the MI than the DMI task (MI > DMI). See Table 2a and Figure 3. Only one cluster located in the middle and superior occipital gyri showed a significant effect in the opposite direction as a main effect (DMI > MI). See Table 2b and Figure S3.

Main effect of visual cues

The main effect of cues activated a wide occipito-temporo-parietal network, including the bilateral superior occipital gyrus, the right superior parietal lobule, the right middle temporal gyrus, the right cuneus, the right lingual gyrus and the right calcarine scissure, being more active in the VC+ than in the VC- conditions (VC+ > VC-). No area showed a significant effect in the opposite direction as a main effect (VC- > VC+). See Table 2c and Figure 4a.

Interaction effect

The ANOVA showed no significant interaction effect Cues × Imagery-type.

Correlation between performance at the TUG task and fMRI activation patterns. The behavioral findings at the TUG task had revealed a less precise coupling between motor execution and motor imagery when subjects performed the MI task with the eyes open. Such coupling is considered an index of the quality of MI (Allali et al., 2014).

In the fMRI data, there was a large pattern of temporo-occipital-parietal extra activity in the imagery tasks performed during eyes-open condition. To evaluate whether this activity predicted the goodness of MI, we did run a correlation analysis between the chronometry ability index and this average BOLD response during the eye-opened MI task.

The average BOLD response of this cluster was extracted by means of the software MARSbar (http://marsbar.sourceforge.net; Brett et al., 2002).

We found that the higher the CA index (in VC+ condition)—that is the less well-coupled execution and imagination—the higher was the BOLD response in the temporo-occipital-parietal cluster that teases apart open-eyed from closed-eyed motor imagery (Two-tailed Pearson's correlation coefficient = .49; $p = .036$). See Figure 4b, first row.

We performed the same analysis for the VC- condition, which did not highlight any significant result (Two-tailed Pearson's correlation coefficient = .23; $p = .23$). See Figure 4b, second row.

4 | DISCUSSION

While it is widely known that mental practice, based on MI, can be a useful training method in different pathological conditions (Lotze & Halsband, 2006), to date it remains unclear how the imagery process can be triggered most effectively for a given behavior in specific populations (for a discussion, see, for example Mulder et al., 2007). This study is part of a broader research plan designed to provide a neuro-functionally informed rationale for the adoption of appropriate imagery techniques to complement rehabilitation practices and prevent the decay of gait-related skills in elderly people or to boost rehabilitation in neurological or orthopedic patients.

TABLE 2 fMRI results of the virtual Walking analysis.

	Left hemisphere					Right hemisphere				
	MNI coordinates					MNI coordinates				
	x	y	z	Z	*p*-value	x	y	z	Z	*p*-value
(a) MI > DMI										
Precentral gyrus (4)	—	—	—	—	—	12	-30	72	3.66	.0001
Supplementary motor area (6)	−6	−2	62	4.51	.000003	6	−20	66	3.89	.00005
	−8	−2	58	4.49	.000004	—	—	—	—	—
	−16	−10	54	3.27	.0005	—	—	—	—	—
Paracentral lobule (4)	−6	−34	66	5.37*	.00000004					
Parietal operculum	−56	−36	24	4.09	.00002	—	—	—	—	—
Supramarginal gyrus	−50	−44	30	4.32	.000008	—	—	—	—	—
	−52	−40	30	4.13	.00002	—	—	—	—	—
Cerebellum_4_5	−20	−36	−28	5.82*	.000000003	22	−36	−28	6.20*	.0000000003
	−20	−48	−28	3.48	.0003	18	−38	−26	6.15*	.0000000004
Cerebellum_3	−6	−40	−22	5.23*	.00000008	8	−40	−24	5.20*	.0000001
Cerebellum_6	−22	−54	−26	3.53	.0002	34	−46	−28	4.77*	.0000009
Vermis_4_5	−2	−52	−10	4.40	.000005	0	−48	−10	4.25	.00001
(b) DMI > MI										
Superior occipital gyrus (19)	—	—	—	—	—	26	−84	24	3.62	.0001
Middle occipital gyrus (19)	—	—	—	—	—	38	−82	12	3.70	.0001
	—	—	—	—	—	42	−78	16	3.66	.0001
Middle occipital gyrus (18)	—	—	—	—	—	30	−84	12	4.12	.00002
(c) VC+ > VC−										
Middle temporal gyrus (37)	—	—	—	—	—	46	−68	4	7.46*	.00000000000004
Superior parietal lobule (5)	—	—	—	—	—	20	−58	58	6.30*	.0000000001
Cuneus (19)	—	—	—	—	—	16	−84	40	5.67*	.000000007
	—	—	—	—	—	12	−82	44	5.53*	.00000002
Superior occipital gyrus (19)	−20	−82	30	Inf*	<.0000000000000006	22	−86	24	Inf*	<.0000000000000006
	−18	−76	44	5.88*	.000000002	26	−84	20	Inf*	<.000000000000001
	—	—	—	—	—	26	−72	28	6.53*	.00000000003
	−12	−94	16	Inf*	<.0000000000000006					
Middle occipital gyrus (18)	−24	−86	16	Inf*	<.0000000000000006					
Lingual gyrus (18)	—	—	—	—	—	12	−72	0	6.89*	.000000000006
	−18	−80	−10	7.14*	.0000000000005	14	−68	−4	6.90*	.000000000003
	—	—	—	—	—	26	−66	−10	6.14*	.0000000004
Calcarine scissure (17)	—	—	—	—	—	8	−78	6	6.98*	.000000000001

*p < .05 FWE corrected at peak level. Inf = Z-score > 8.

In our previous studies, we found that (a) MI of gait maps in a meaningful way onto the visuo-motor brain systems (Sacheli et al., 2017), identified by 18F-FDG PET activation experiments on explicit gait (la Fougere et al., 2010), (b) aging is associated with increased functional demands on these motor networks for the mere task of foot movement execution (Sacheli et al., 2020) and (c) peripheral deficits of gait due to knee-arthritis are associated with reduced MI abilities for gait accompanied by impoverished activation of MI specific networks (Sacheli et al., 2018).

Here we investigated the behavioral and neurofunctional effects of visual-cues on motor imagery (MI) of gait.

Previous research suggested that external cues can facilitate the actual physical execution of motor acts (Verschueren et al., 1997); it remains to be seen to what extent the presence of such external cues may provide an additional benefit on the use of MI as a rehabilitation tool. In principle, one may speculate that such visually enriched scenarios may inevitably lead to better outcomes with imagery because they mimic real life settings more closely. If so, one should find better

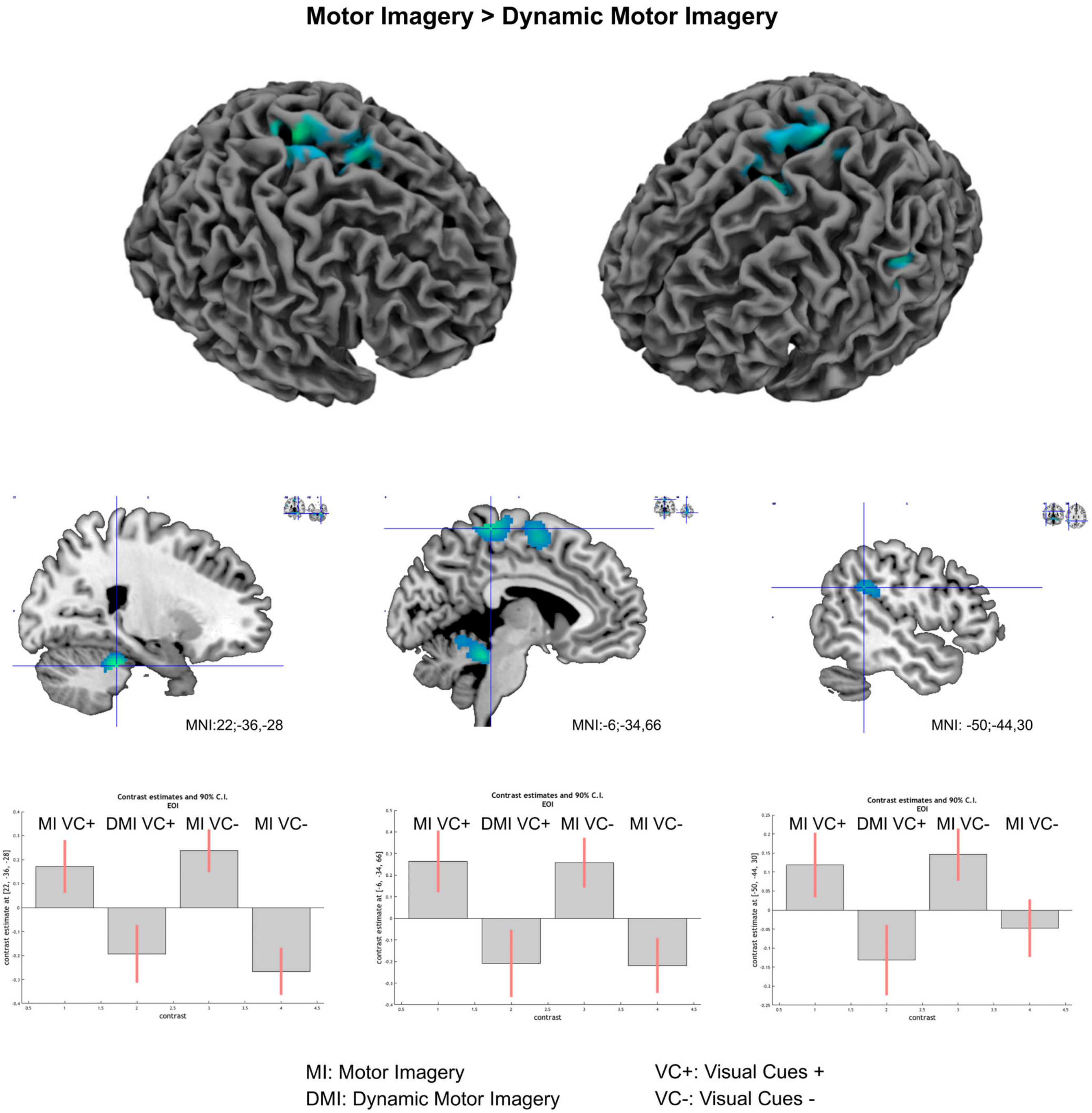

FIGURE 3 fMRI results for the main effect of MI > DMI in Experiment 2

results in tasks measuring how good MI for gait is. Again, in principle, the presence of visual cues should have a sizeable impact on the functioning of relevant neural networks helping in tightening up the co-activation of strictly motoric brain networks involved in the control of the lower-limbs and those concerned in monitoring of external visuo-spatial cues typical of the gait activity and navigation. The aforementioned predictions, however, may not hold as well for elderly people who typically suffer in the integration of rich multi-dimensional scenarios (Lester, Moffat, Wiener, Barnes, & Wolbers, 2017).

To address these issues, we combined the best of two worlds, a clinical task that is widely used and permits to measure the coupling with actual execution of gait under controlled conditions and an fMRI gait imagery paradigm that we validated in the recent past and that permits to depict the brain networks involved in gait imagery.

In a nutshell, the evaluation of the aforementioned questions with these tools showed that, contrary to expectation, elderly subjects have a better quality of gait imagery when performing the task with the eyes-closed. This data has been replicated in two independent

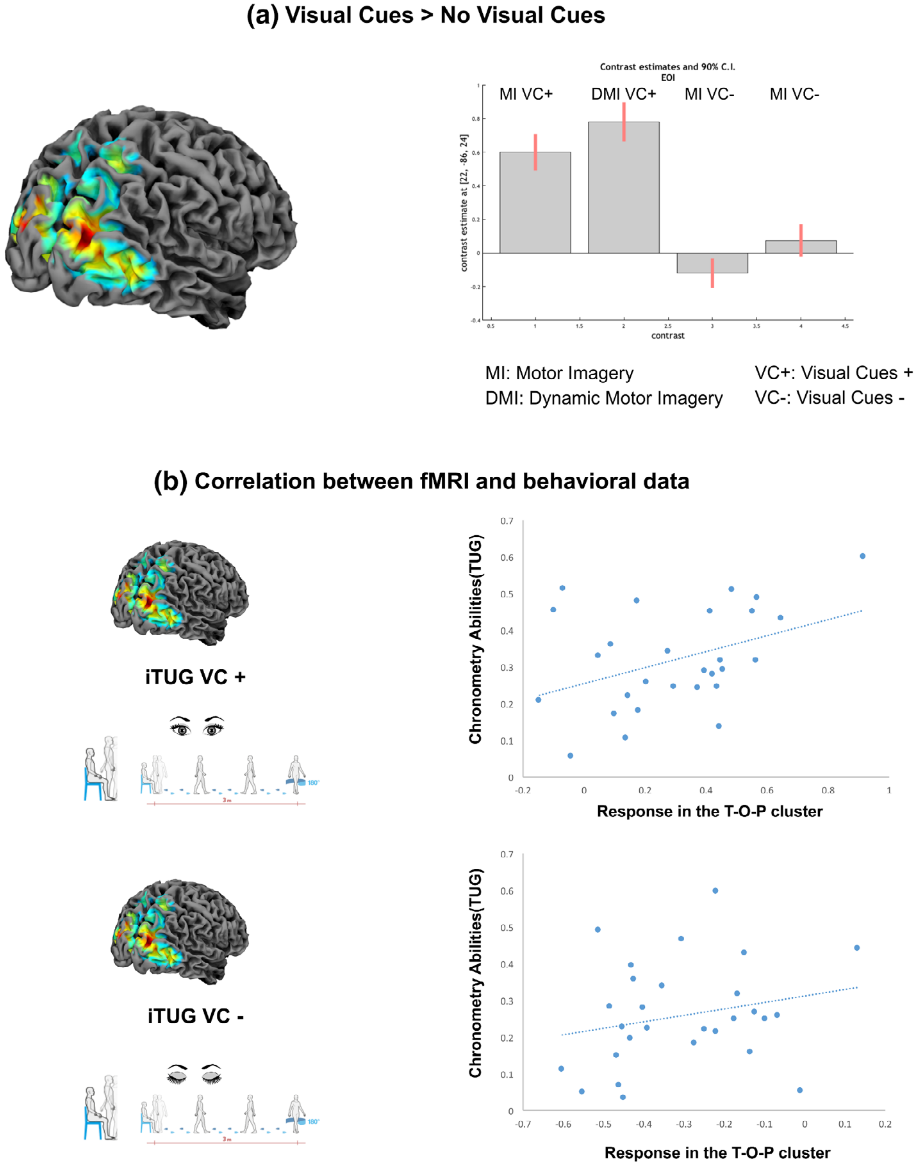

FIGURE 4 (a) fMRI results for the main effect of VC+ > VC-. The graph on the right illustrates the activations in the local maxima located in the right superior occipital gyrus (MNI 22, -86, 24); (b) Correlation between the activations in the temporo-occipito-parietal (T-O-P) cluster (VC+ condition) and the behavioral performance (chronometry abilities index recorded during the iTUG VC+ condition)

samples. Neurofunctional data collected in one of such samples revealed the expected additional activations of visual temporo-occipito-parietal cortices for the open-eyed imagination. No substantial visual cues effects were found in gait specific motor system (also identified with explicit foot movement conditions). Importantly, the higher was the activity in these posterior cortices during the eyes-open condition, the lower was the temporal coupling between gait motor execution and gait motor imagination. This suggests that when participants are more focused on the visual features of the scenario, they are less accurate in monitoring the timing of their motor performance. The relevance of these findings is discussed below.

4.1 | Behavior

As said, the behavioral effects of having the eyes open or shut during gait imagery was tested with the Timed Up & Go task (TUG Podsiadlo & Richardson, 1991), a popular and validated clinical tool used for the assessment of real and imagined gait abilities. The coupling between actual execution and imagery of the task, an index of the quality of the MI process (Allali et al., 2014), was less tight when participants were allowed to visually explore the environment during gait imagination. This effect was replicated in two independent samples of older participants, confirming the disadvantage of keeping eyes open during the Timed Up & Go task in its imagery form.

This finding conflicts with the results of Heremans and collaborators (2009), who reported that visual cues improved the quality of MI. These contrasting results might be explained by the substantial differences in the experimental paradigms and the dependent variable of choice. Heremans and collaborators (2009) instructed their subjects to execute and then imagine, with or without visual control of their upper limb, cyclic wrist movements directed to specific visual targets. They found a better coupling between eye movements and wrist movements in the open-eyed condition. Most likely, the inclusion of a reaching component in the task made direct visual exploration more efficient there, a situation very different from our imagined TUG. Moreover, they used eye movements and subjective imagery vividness as indexes of the MI ability, while we focused on the temporal similarities between movement and imagination (Heremans et al., 2009).

Why should the imagined TUG be less precise with eyes open? While we do not have a mechanistic explanation for this, we suggest that this might be attributed to the processing load implied in visual exploration and scanning of the environment. This might have a distracting impact on processing of motoric and proprioceptive information and temporal appreciation of the duration of the walking task.

However, when explicitly asked about the perceived quality of their MI abilities in the VC+ and VC- conditions, our subjects reported an equal level of perceived imagery vividness. Thus, while chronometric MI data supported the disadvantage of imaging while keeping eyes open, self-report data did not highlight any difference. The dissociation between implicit and explicit measures of MI abilities has been already shown in previous studies. For example, Williams and colleagues (Williams, Guillot, Di Rienzo, & Cumming, 2015) showed the lack of correlations between self-report and mental chronometry measures for either external, internal and kinesthetic imagery. The authors explained this inconsistency as an evidence of the complementary nature of the two measures. A lack of association between objective and subjective quality of MI is also reported in recent Brain-Computer Interface studies focused on MI. For example, Rimbert, Gayraud, Bougrain, Clerc, and Fleck (2018) showed no significant correlation between MI performance (measured by taking into account the average classification accuracy on EEG data between right-hand MI and a rest period) and the scores obtained at the Motor Imagery Questionnaire Revised-Second Edition (Rimbert et al., 2018).

This finding suggests that introspective methods cannot adequately capture the differences between modalities that can instead be described by more objective chronometric measures.

How could such behavioral findings be mirrored in a meaningful way by fMRI observations? One obvious way would have been to observe an interaction between keeping the eyes open or shut and the activation of the gait motor system and its interface with temporo-occipito-parietal visual monitoring system during imagery whereby the gait motor system is "more active" while subjects were keeping their eyes closed. As we discuss below, there was another possibility for which we have explicit evidence.

4.2 | fMRI

At the neurofunctional level, we observed the expected activation of the brain network involved in gait control, for both the MI performed with eyes open, while observing a video simulating a stroll along a path, and for the MI performed with the eyes shut. The main effect defined by the imagery type contrast (MI > DMI) revealed the recruitment of premotor areas, parietal and cerebellar regions, in line with what we reported in our previous studies on MI of gait in an independent sample of elderly subjects (Sacheli et al., 2017). The comparison of this pattern with the one derived from our separate analysis on explicit ankle dorsiflexion, allows us to confirm that the areas involved in gait motor planning seen in the MI task do belong to the circuit responsible for the execution of foot movements. Moreover, the brain activation patterns identified by the comparison MI > DMI were very similar for both an open-eyed (VC+) and eye-shut (VC-) condition, as no interaction could be found between MI type and eyes open or closed. Indeed, once overt foot movements were controlled for with the Dynamic MI (DMI) task and its baseline, we found the involvement of the motor network for gait control, independently from the presence of visual cues.

How could we then reconcile the fMRI data with the behavioral data of the Timed Up & Go task?

Before moving into the details, it is worthy to note that the behavioral and the fMRI tasks are not perfectly matched; in particular, the TUG/iTUG task in its VC+/ VC- version lacks some experimental features: in the VC+ condition of the iTUG task, subjects simply observed a stationary scenario, while in the fMRI VC+ task the scene was moving dynamically. Moreover, admittedly, we did not have a precise behavioral counterpart (a task performed outside the scanner) for the DMI task performed during fMRI. We believe that the main effect differences between VC+ and VC- might be sufficient to explain the behavioral observation that MI for gait has a better chronometric coupling with gait execution.

The VC+ and VC- conditions differed for a vast temporo-occipito-parietal additional activation for open-eyed MI as a main effect. It is worthy to note that both conditions had a matched baseline that involved imagining standing on a spot. Thus, the activations shown in VC+ condition highlight the brain regions that were significantly more active during MI associated with visual cues of a dynamic scenario as compared with the visual cues for imagery of standing on the spot while observing a stationary scenario. Hence, these results might be explained by the complexity of the visual stimulation elicited by the virtual walking dynamic scenarios while keeping the eyes open. Temporo-parietal regions are involved in the modulation of gait patterns in response to environmental cues to integrate body movements with the environment in order to navigate the external world (Boccia, Nemmi, & Guariglia, 2014). The recruitment of posterior multisensory regions might be particularly relevant in the elderly (Zwergal et al., 2012) to support motor performance and handle with age-related sensory system decline (for similar interpretations in different contexts, see (Heuninckx, Wenderoth, Debaere, Peeters, & Swinnen, 2005).

These considerations inevitably lead to propose that the extra-processing load imposed by dealing with dynamic visual information, and the associated neural labor, might be a sufficient explanation for the less precise appreciation, during a chronometry task, of the time needed to perform a motor task in real life. However, we have more explicit evidence in defense of this proposal: the activity of regions that differentiate the VC+ and VC- was higher the more imprecise were the participants in mentally judging the time needed to complete the motor task Timed Up & Go task. Of course, this is not a direct correlation between a behavioral index collected during fMRI: the CA index should be rather seen as a phonotypical profile of the accuracy of each individual in judging the time of imagination in relation with the same time for motor execution. In this sense, the correlation is less circular, because the behavior was not collected during the scans; rather, the correlation suggests that the more one relies on visual information during motor imagery (larger activation of the posterior cortices) the more inaccurate one is in estimating the time needed to perform the TUG task during imagination.

These observations are overall consistent with what we described in previous experiments on explicit MI of hands movements, where the lower was the quality of the MI process in elderly subjects, the greater was the recruitment of posterior brain regions: in Zapparoli et al. (2013), for example, we found that the temporal discrepancy between MI and ME of hand movements in elderly subjects correlated with the activity of occipital lobe brain regions.

4.3 | Implications for motor neurorehabilitation of gait and conclusions

We conclude that both visually-cued and internally-cued MI are associated with the activation of gait specific motor circuits. The less precise behavioral temporal coupling between imagined and executed gait while keeping eyes open may be attributed to the processing load implied in visual monitoring of the environment, associated with a large bilateral occipito-temporo-parietal activation.

These observations have some implications for the rehabilitation of gait using motor imagery. Having shown that for elderly subjects the addition of visual cues from the environment results in a decrease of the MI accuracy, should we discourage the use of visual cues in MI once and for all? Of course not.

Rehabilitation is a dynamic process, in which one tries to reinforce and reassemble the different building blocks of a function in a working functional chain (Mirelman, Shema, Maidan, & Hausdorff, 2018). Gait is a complex behavior that fits ideally with this description. In essence, it is made of several components, some more bodily centered and based on kinesthetic motoric information, other related to the monitoring of the external world, both concerned with their mutual integration. Let us consider a prototypical working example, the rehabilitation of gait after immobilization following a hip-fracture: the reinforcement of bodily centered motor awareness and strength is one primary goal in this rehabilitation preliminary to the training of real-life gait. In this perspective, our evidence suggests that eyes-shut motor imagery may serve better to efficiently regain bodily centered motor awareness as people are more accurate in simulating gait with comparison to their actual performance. Eyes-opened imagery may prove more useful when trying to connect elementary motor skills to the real-life needs of walking in a free environment. Both forms might be used with different interconnected goals. Finally, our evidence does not deny the possibility that MI with visual cues might be a strategy of choice in other situations. For example, in movement disorders of central origin, like Parkinson's disease (Heremans, Nieuwboer, Feys, et al., 2012) or multiple sclerosis (Heremans, Nieuwboer, Spildooren, et al., 2012), motor imagery with visual cues proved beneficial possibly because the visual cues, with dynamic components, by-pass a limited ability of self-induced retrieval of motor plans.

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CONFLICT OF INTEREST

Authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data are available upon request to the corresponding author (L. Z.).

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