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Temporal features of imagined locomotion in normal aging

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ABSTRACT

Motor imagery is the ability to mentally simulate a movement without executing it. Previous investigations have reported a deterioration of this ability during complex arm movements in aged adults. In the present study, we aimed to extend these findings by investigating the temporal features of imagined precision gait in healthy elderly adults. Locomotion is a unique example of imagined movement because it involves simulated full-body movement and the concurrent updating of environmental spatial information. Nine young and nine older adults actually or mentally walked (walking distance: 5 m) along three paths having different widths (15 cm, 25 cm, and 50 cm). The narrowest path required balance control and accurate foot placement. We used the mental chronometry paradigm, notably the temporal similarity between actual and imagined movements, as an indicator of the accuracy of the motor imagery process. Our findings indicated that while motor imagery ability was preserved in the young group whatever the width of the path, it was significantly deteriorated in the elderly group. Aged adults systematically overestimated the duration of imagined movements with respect to those of executed movements. Moreover, paths width negatively influenced the motor imagery performances in the elderly group. We assume that motor imagery decline may reflect functional changes in the aging brain, and could be a clinical tool to detect deteriorations in motor planning and prediction in aged adults.

Motor imagery is a mental process during which a subject internally simulates a movement without any corresponding motor output. Neurophysiological studies have reported that similar neural networks are recruited during imagined and executed motor actions [5,7,9,18,29]. Furthermore, psychophysical experiments have shown that imagined and executed movements preserve the same spatiotemporal characteristics, suggesting thus that covert and overt stages of actions share similar motor representations [4,6,14,18,20,21].

Similar temporal features between executed and imagined movements are provided by internal forward models that are engaged in both physically executed and mentally simulated motor actions [3,6,21,31]. Forward internal models mimic the causal flow of the physical process by predicting the future sensorimotor state (e.g. position, velocity) given the efferent copy of the motor command and the current state. During motor imagery, precise timing information for the movement being imagined is provided by the sensorimotor predictions of the internal forward model on the basis of the correctly prepared, but blocked motor commands. Although strong temporal similarities characterize executed and imagined movements in young adults, a progressive weakness of this temporal relationship has been observed in aged adults. In general, elderly adults underestimate imagined arm movements compared to their executed counterparts [22,23,27,28]. Temporal imprecision in motor imagery increases when the motor task involves high spatiotemporal (i.e., spatial accuracy associated to high arm movement velocity) and/or dynamic (arm motion against inertial loads) constraints. We have previously proposed that the decline in motor imagery ability in the elderly could be explained by the fact that predictive models lose their accuracy with advance in age [22,23,27,28]. In the current study, we wanted to validate this hypothesis and to expand our previous results. Since earlier investigations have mainly examined upper arm movements in the elderly [22,23,27,28], here we investigated walking movements. Locomotion is a unique example of imagined movement because it involves simulated full-body movement and the simultaneous update of environmental spatial information. We asked young and aged adults to actually walk and to imagine walking along three different paths. Each path had a different width which determined the spatial constraint, and thus the task complexity. As our general hypothesis is that there is a general decline in motor imagery ability in elderly, we expected that motor imagery performance will be poorer in aged subjects. We further expected that the motor

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imagery performance in the elderly will be inversely related to the increase in task difficulty.

Eighteen adults participated in the present study after giving their written consent. The regional ethics committee of Burgundy (C.E.R.) approved the experimental protocol which was carried out in agreement with legal requirements and international norms (Declaration of Helsinki, 1964). Participants were divided into two different groups according to their age: (i) the young group ($n = 9$; 3 males and 6 females; mean age: 25.5 ± 2.5), and (ii) the elderly group ($n = 9$; 3 males and 6 females; mean age: 71.4 ± 3.2). All participants were in good health, with normal or corrected vision, and did not present any neurological, muscular or cognitive disorders. The elderly participants were all retired, had a regular physical activity (~1.5 h 2 days per week, approved by a medical doctor) and at least one daily cognitive activity (reading newspapers, crosswords or literature). Their cognitive capacities were also evaluated by means of the mini mental state examination test (all scores $\geq$28). All participants received complete information about the experimental procedures, but none of them was informed of the aim of the experiment.

The experiment took place in a sound-isolated room which was temperature regulated (22 ± 2 °C), and illuminated with homogeneous white light. The ground was smooth and plain. Three walking paths were drawn on the ground, and two lines, drawn perpendicularly to these paths, indicated the starting and the finishing areas (walking distance, 5 m). Path widths determined the level of spatial constraints (widths: 15 cm, 25 cm, and 50 cm). The narrowest path required an accurate feet placement, that is, one foot in front of the other. This spatially constraint locomotion implies, notably in aged people, the preservation of equilibrium and the mobilization of important cognitive resources [2,11,17,26,32]. The other paths, from the broader- to the broadest path, progressively allowed the adoption of a normal gait.

Participants were standing upright behind the starting line; their arms were hanging along the body, and their feet were parallel and slightly apart (see Fig. 1). They were requested to physically or to mentally walk through the different paths. We took care to limit the risks of falling, notably in aged participants, by proposing locomotion at a natural self-selected speed. Participants were further asked to physically or mentally perform the task very precisely, i.e., without walking on the lines limiting the paths. They were informed that if they walked on the lines during an executed movement, the trial would be cancelled and performed again. Due to this restriction, a small number of trials were repeated. Precisely, 10 trials (2.7% of the total number of trials) were repeated by the young group and 12 trials (representing 3.3% of the total number of trials) were repeated by the elderly group. After each executed trial, the participants came back to the starting area by walking outside the paths. For the imagined trials, we emphasized to the participants that they must feel themselves performing the task (motor imagery in a first person perspective) rather than watching themselves doing it (visual or external imagery). All the participants verbally reported at the end of the experiment that they imagined walking at a first person perspective, and that they respected the requirements for spatial accuracy. In this condition, the participants were motionless at the starting position, and imagined themselves walking through the path. Vision was allowed in order to facilitate the visualization of the path.

Each participant performed 12 trials in each experimental condition; that is a total of 72 trials (12 trials × 2 movement conditions (executed, imagined) × 3 path widths (15, 25, and 50 cm)). The trials were accomplished at two different sessions (36 trials per session) separated by a time interval of 48 h. During each session, executed and imagined trials were presented to the participants at two different blocks: the executed block (EB) and the imagined block (IB). Within each block, the three paths were randomly presented to the participants. In the first session, the IB was performed before the EB, while in the second session the EB was performed before the IB. Five minutes separated the two blocks. Furthermore, when a participant performed 10 consecutive trials, he (she) rested for ~1 min to avoid physical and mental fatigue. In order to familiarize themselves with the experimental protocol, all participants performed one executed and one imagined trial in each path. No information concerning their temporal performance was given to the participants during the practice or the experimental trials.

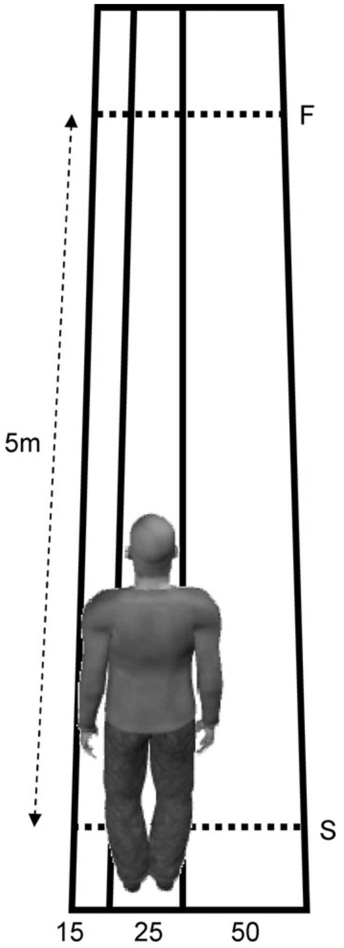

Fig. 1. Motor task. The participants were standing upright behind a start line (S), in front of one of the three paths: the broadest path (width = 50 cm), the middle path (width = 25 cm) or the narrowest path (width = 15 cm). They had to walk or to imagine walking (distance 5 m) through the paths from the start (S) to the finish line (F).

The duration of executed and imagined trials was recorded by means of an electronic stopwatch (temporal resolution: 10 ms). Before each trial, the participants remained immobile at the starting position. After a variable temporal interval, between 2 and 3 s, an auditory cue was given as the starting signal for each executed or imagined trial and the experimenter started the temporal acquisition. After this cue, the participants started walking, or imagined walking, through the path. When the participants' shoulders physically or mentally crossed the vertical plane of the finishing line, they verbally indicated (by saying "stop") the end of the trial to the experimenter who stopped the temporal acquisition. The time that had elapsed between the auditory cue and the end of the trial corresponded to the movement duration.

For each participant we calculated the average durations of executed and imagined movements for each path separately. To

Table 1
Executed and imagined movement durations.

	Path 1	Path 2	Path 3
Executed			
Elderly	5.25 (±0.26)	5.54 (±0.33)	6.18 (±0.44)
Young	5.67 (±0.38)	5.68(±0.38)	5.02 (±0.44)
Imagined			
Elderly	7.15 (±1.04)	8.37 (±1.51)	10.00 (±1.86)
Young	5.41 (±0.37)	5.67 (±0.38)	6.18 (±0.51)

The average movement durations (s) and standard errors (±SE) are presented for each group (young, elderly), movement condition (executed/imagined) and path width (path 1: 50 cm; path 2: 25 cm; path 3: 15 cm).

examine participants' imagery performance, we calculated an index of performance (IP):

$$\mathrm{IP} = \frac{\mathrm{MD_E} - \mathrm{MD_I}}{\mathrm{MD_E}} \times 100$$

The IP is defined as the difference between the average duration of executed movements ($\mathrm{MD_E}$ in the formula; $n = 12$) and the average duration of imagined movements ($\mathrm{MD_I}$ in the formula; $n = 12$). In order to account for inter-individual differences in movement duration, we divided for each participant this value by the average executed movement duration ($\mathrm{MD_E}$). The IP index indicates whether subjects overestimate (negative values) or underestimate (positive values) movement durations during motor imagery. An index near to zero would indicate a good imagery performance. However, this index could mask differences between imagined and actual movement durations. This is notably the case, if some subjects underestimate and others overestimate movement durations during motor imagery. In order to provide a more complete analysis of motor imagery performance, we also calculated the absolute IP ($\mathrm{IP_{abs}}$).

The variables did not show normal distributions (Shapiro-Wilk *W*-test), and therefore, we used non-parametric tests. We performed Mann–Whitney *U*-tests for between-group comparisons (young versus aged), and Wilcoxon tests for within-group comparisons (path width: 15, 25, and 50; session: I–E versus E–I). The level of significance was $p < 0.05$.

Table 1 illustrates the average durations (±SE) for the executed and imagined walking movements. Durations of executed movements did not statistically differ between the two groups for the three path widths (for all comparisons, $p > 0.5$). For the young group, executed and imagined walking durations were equivalent, and did not differ with path width (for all comparisons, $p > 0.1$). However, this was not the case for the elderly group. Imagined walking was significantly longer than actual walking for the three locomotor paths ($p < 0.02$ for all comparisons). Furthermore, in the aged group, both imagined and actual walking durations increased when locomotor path widths decreased ($p < 0.05$ for all comparisons). These results are reflected in the analysis of the IP (see Fig. 2). Elderly adults significantly overestimated the duration of imagined movements. This was not the case of young adults, whose imagined movement durations were near to zero, indicating good imagery performance ($p < 0.01$ for all the comparisons between young and elderly). In addition, IP values for the aged group significantly increased when path width decreased ($p < 0.05$). We did not find any modulation of the IP with the path width for the young group ($p > 0.05$ for all comparisons). The values of $\mathrm{IP_{abs}}$ were significantly greater for the elderly compared to the young group ($p < 0.01$ for all path widths). In addition, $\mathrm{IP_{abs}}$ values increased when path width decreased for the aged group (on average, 31.70 ± 12.18, 43.17 ± 15.72, and 54.32 ± 16.77 for the 50 cm, 25 cm and 15 cm widths, respectively; $p < 0.05$ for all comparisons). We did not find any modulation of the $\mathrm{IP_{abs}}$ values according to the path width for the young group (on average, 6.24 ± 1.67, 7.71 ± 1.83 and 9.22 ± 4.04 for the 50 cm, 25 cm and 15 cm widths, respectively; $p > 0.05$ for all comparisons).

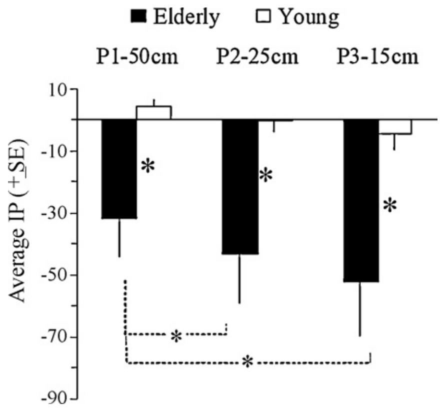

Fig. 2. Index of performance (IP). The average (±standard error) IPs, indicating the normalized difference between the executed and the imagined movement durations, are illustrated for each group (young, elderly) and path widths (P1, P2, P3). The stars (*) represent significant differences ($p < 0.05$).

In the current study, we explored motor imagery of normal and precision gait in young and elderly adults. By comparing the temporal features of executed and imagined walking, we found that isochrony was not respected in aged participants. Furthermore, the decline in the quality of imagined walking, investigated by the index of motor imagery performance (IP and $\mathrm{IP_{abs}}$), was increased when the spatial precision required to perform the task increased. These findings indicate that motor imagery ability is significantly deteriorated in the elderly.

We found that walking times increased from the broader to the narrower path in the aged group. This finding corroborated previous results which showed that normal ageing influences postural control and body equilibrium [12,16,19], and may suggest that movement control could be more challenging for aged people when walking on a narrow path. We observed that imagined movement times were also affected by the path width. This result indirectly supports our claim that elderly adults internally simulated, in a first person perspective, their walking movements by taking into account the spatial constraints of the task. However, they overestimated these constraints because imagined walking times were significantly longer than actual walking times. It seems, therefore, that elderly people cannot make accurate predictions of their body motion in a particular context.

In addition to the finding presented above on actual and imagined locomotion, other behavioural tasks have led to similar conclusions. Chronometric data suggests that the timing of actual and imagined arm pointing movements is dissimilar in elderly subjects. Pointing to spatial targets of different widths or making reaching movements in a changing gravito-inertial context significantly affected the timing of imagined arm movements [22,23,28]. Taken together, these findings may suggest an alteration of internal models of action in the elderly.

The neural control of gait requires interactions between locomotor rhythm generation, balance control, and adaptation of the movements to the environmental context. The act of imagined walking is especially interesting for a broad understanding of motor imagery because it extends beyond body-part movement requiring the representation and updating of environmental space. Imagined walking in young adults requires the activation of several brain areas. Malouin et al. [13] have reported the activation of the precuneus and dorsal premotor cortex bilaterally, the left dorsolateral prefrontal cortex, the left inferior parietal lobule, and finally the right posterior cingulate cortex. These structures are part of a well-documented neural network [9] associated with visuo-spatial processing of motor actions in space, the planning of sequential movements and their motor simulation from a first person perspective. Bakker et al. [1], by exploring brain activity during motor imagery of precision gait in young adults, found that the activity and the inter-regional couplings between bilateral superior parietal lobule, the dorsal precentral gyri, and the right superior middle occipital gyrus were modulated by the degree of spatial accuracy of the imagined gait, i.e., when subjects imagined walking along a narrow path requiring accurate positioning of each foot. Up to now, data reporting brain activation during simulated actions in elderly subjects do not exist. It would be interesting to compare imaging with psychophysical data in elderly people. The existing data, regarding brain activation in elderly people during actual hand movements, led us to speculate that our behavioural findings related to imagined actions could be attributed to structural and functional changes that occur with age at the level of the CNS (for review see [24,25]). Underactivation and overactivation of brain areas are the most prominent functional changes, suggesting non-selective brain activation, compensation or dedifferentiation processes within the aging brain [8,10,15,24,30]. The alteration of the time processing of imagined actions in elderly adults is in congruence with the current vision of the aging mind. It further proposes a progressive decline on the generation and control of intended but not executed actions in the aging brain. However, at present, it is hard to affirm that these results indicate a direct effect of normal aging on internal predictive models. Normal aging influences cognitive and motor abilities in latter life, and, therefore, could also influence predictive processes [24,25]. The finding that motor imagery deteriorates with age has also clinical implications. We propose that motor imagery could be an interesting tool for the timely detection of a decline in motor planning and prediction in elderly subjects.

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References

[1] M. Bakker, F.P. De Lange, R.C. Helmich, R. Scheeringa, B.R. Bloem, I. Toni, Cerebral correlates of motor imagery of normal and precision gait, NeuroImage 41 (2008) 998.

[2] L. Bernard-Demanze, M. Dumitrescu, P. Jimeno, L. Borel, M. Lacour, Age-related changes in posture control are differentially affected by postural and cognitive task complexity, Curr. Aging Sci. 2 (2009) 139–149.

[3] G. Courtine, C. Papaxanthis, R. Gentili, T. Pozzo, Gait-dependent motor memory facilitation in covert movement execution, Brain Res. Cogn. Brain Res. 22 (2004) 67–75.

[4] J. Decety, M. Jeannerod, Mentally simulated movements in virtual reality: does Fitts's law hold in motor imagery? Behav. Brain Res. 72 (1995) 127–134.

[5] H.H. Ehrsson, S. Geyer, E. Naito, Imagery of voluntary movement of fingers, toes, and tongue activates corresponding body-part-specific motor representations, J. Neurophysiol. 90 (2003) 3304–3316.

[6] R. Gentili, V. Cahouet, Y. Ballay, C. Papaxanthis, Inertial properties of the arm are accurately predicted during motor imagery, Behav. Brain Res. 155 (2004) 231–239.

[7] E. Gerardin, A. Sirigu, S. Lehericy, J.B. Poline, B. Gaymard, C. Marsault, Y. Agid, D. Le Bihan, Partially overlapping neural networks for real and imagined hand movements, Cereb. Cortex 10 (2000) 1093–1104.

[8] S. Heuninckx, N. Wenderoth, F. Debaere, R. Peeters, S.P. Swinnen, Neural basis of aging: the penetration of cognition into action control, J. Neurosci. 25 (2005) 6787–6796.

[9] M. Jeannerod, Neural simulation of action: a unifying mechanism for motor cognition, Neuroimage 14 (2001) S103–S109.

[10] J.M. Logan, A.L. Sanders, A.Z. Snyder, J.C. Morris, R.L. Buckner, Under-recruitment and nonselective recruitment: dissociable neural mechanisms associated with aging, Neuron 33 (2002) 827–840.

[11] L. Lundin-Olsson, L. Nyberg, Y. Gustafson, "Stops walking when talking" as a predictor of falls in elderly people, Lancet 349 (1997) 617.

[12] B.E. Maki, W.E. McIlroy, Postural control in the older adult, Clin. Geriatr. Med. 12 (1996) 635–658.

[13] F. Malouin, C.L. Richards, P.L. Jackson, F. Dumas, J. Doyon, Brain activations during motor imagery of locomotor-related tasks: a PET study, Hum. Brain Mapp. 19 (2003) 47–62.

[14] P. Maruff, P.H. Wilson, J. De Fazio, B. Cerritelli, A. Hedt, J. Currie, Asymmetries between dominant and non-dominant hands in real and imagined motor task performance, Neuropsychologia 37 (1999) 379–384.

[15] V.S. Mattay, F. Fera, A. Tessitore, A.R. Hariri, S. Das, J.H. Callicott, D.R. Weinberger, Neurophysiological correlates of age-related changes in human motor function, Neurology 58 (2002) 630–635.

[16] F. Mourey, A. Grishin, P. d'Athis, T. Pozzo, P. Stapley, Standing up from a chair as a dynamic equilibrium task: a comparison between young and elderly subjects, J. Gerontol. A: Biol. Sci. Med. Sci. 55 (2000) B425–B431.

[17] T. Mulder, W. Zijlstra, A. Geurts, Assessment of motor recovery and decline, Gait Posture 16 (2002) 198–210.

[18] J. Munzert, B. Lorey, K. Zentgraf, Cognitive motor processes: the role of motor imagery in the study of motor representations, Brain Res. Rev. 60 (2009) 306–326.

[19] C. Paizis, C. Papaxanthis, B. Berret, T. Pozzo, Reaching beyond arm length in normal aging: adaptation of hand trajectory and dynamic equilibrium, Behav. Neurosci. 122 (2008) 1361–1370.

[20] C. Papaxanthis, T. Pozzo, R. Kasprinski, A. Berthoz, Comparison of actual and imagined execution of whole-body movements after a long exposure to microgravity, Neurosci. Lett. 339 (2003) 41–44.

[21] C. Papaxanthis, M. Schieppati, R. Gentili, T. Pozzo, Imagined and actual arm movements have similar durations when performed under different conditions of direction and mass, Exp. Brain Res. 143 (2002) 447–452.

[22] P. Personnier, Y. Ballay, C. Papaxanthis, Mentally represented motor actions in normal aging: III. Electromyographic features of imagined arm movements, Behav. Brain Res. 206 (2010) 184–191.

[23] P. Personnier, C. Paizis, Y. Ballay, C. Papaxanthis, Mentally represented motor actions in normal aging II. The influence of the gravito-inertial context on the duration of overt and covert arm movements, Behav. Brain Res. 186 (2008) 273–283.

[24] P. Reuter-Lorenz, New visions of the aging mind and brain, Trends Cogn. Sci. 6 (2002) 394.

[25] P.A. Reuter-Lorenz, C. Lustig, Brain aging: reorganizing discoveries about the aging mind, Curr. Opin. Neurobiol. 15 (2005) 245–251.

[26] E. Scherder, L. Eggermont, D. Swaab, M. van Heuvelen, Y. Kamsma, M. de Greef, R. van Wijck, T. Mulder, Gait in ageing and associated dementias; its relationship with cognition, Neurosci. Biobehav. Rev. 31 (2007) 485–497.

[27] X. Skoura, C. Papaxanthis, A. Vinter, T. Pozzo, Mentally represented motor actions in normal aging. I. Age effects on the temporal features of overt and covert execution of actions, Behav. Brain Res. 165 (2005) 229–239.

[28] X. Skoura, P. Personnier, A. Vinter, T. Pozzo, C. Papaxanthis, Decline in motor prediction in elderly subjects: right versus left arm differences in mentally simulated motor actions, Cortex 44 (2008) 1271–1278.

[29] A.J. Szameitat, S. Shen, A. Sterr, Motor imagery of complex everyday movements. An fMRI study, Neuroimage 34 (2007) 702–713.

[30] N.S. Ward, R.S. Frackowiak, Age-related changes in the neural correlates of motor performance, Brain 126 (2003) 873–888.

[31] D.M. Wolpert, Z. Ghahramani, Computational principles of movement neuroscience, Nat. Neurosci. 3 (Suppl.) (2000) 1212–1217.

[32] M. Woollacott, A. Shumway-Cook, Attention and the control of posture and gait: a review of an emerging area of research, Gait Posture 16 (2002) 1.