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Is somatosensory excitability more affected by the perspective or modality content of motor imagery?

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ABSTRACT

Beneficial effects of mental practice likely arise because motor imagery involves largely similar neural networks as physical execution of the same movement. While it is known that the involvement of the motor system is favoured by focusing on the kinaesthetic modality and by the first person perspective, little is known about the impact of these factors on the somatosensory system. The present paper examines the effects on the somatosensory excitability of both perspective (the point of view of the person imagining a motor act) and modality (visual versus kinaesthetic) during mental practice. Seventeen healthy subjects participated. Quality of mental practice was controlled using chronometric tests and a subjective questionnaire. Excitability of the somatosensory system was assessed through the steady-state electroencephalographical response to a continuous train of electrical stimuli applied to the radial nerve, at the same time subjects were instructed to perform one of five tasks designed to separate the effects of perspective, modality and motor versus non-motor imagery. Kinaesthetic motor imagery exerts the largest effect on somatosensory excitability whereas visual motor imageries (1st and 3rd person perspectives) produce the same lower effect that static visual imagery does. Strikingly, specific effect of kinaesthetic motor imagery correlates with the selfselected speed to imagine and execute the same movement. These findings suggest a key role of the kinaesthetic content of motor imagery in recruiting the sensorimotor system.

Motor imagery (MI) is defined as an active process during which the representation of an action is internally reproduced without any overt output [5]. Mental practice, the repetition of imagined motor acts [15], is more and more recognized as a training approach in neurorehabilitation [2,7,9,26]. Beneficial effects of mental practice through MI likely arise from the numerous features that MI shares with the execution of physical movement. Indeed, the duration of imagined movements correlates with the duration of real movements; MI evokes similar responses from the autonomic nervous system; and, more importantly, the imagination of an action involves largely similar neural networks as its physical execution (for reviews, see [13,17,24]).

The content of MI includes two main aspects: the perspective and the modality. Perspective refers to the point of view of the person imagining a motor act: does she/he imagine her/his own body moving (1st person perspective) or does she/he imagine the body movement of someone else (3rd person perspective)? Modality refers to the fact that the focus may be turned either on one (visual) or another (kinaesthetic) sensory modality. Visual MI is usually considered to be easier to evoke, but kinaesthetic MI may be more closely related to the motor processes [33,34]. Visual MI involves either perspective whereas kinaesthetic MI implicates the 1st person perspective only. While the 1st person perspective can involve both modalities, the 3rd person perspective implicates only the visual modality. In other words, visual MI cannot be strictly orthogonal to kinaesthetic MI, at least when the focus is on the 1st person perspective or not clearly specified.

Neuroimaging studies have demonstrated that, when imagining, imitating and observing a movement, the 1st person perspective activates more the sensorimotor system than the 3rd person perspective [16,18]. In the same vein, kinaesthetic MI has been shown to recruit more motor-related neural substrates than

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visual MI [14,33,34]. To our knowledge, however, no study has made a direct comparison of both perspective and modality in the same subjects. Thus, the relative contribution of perspective and modality remains unclear. Based on previous studies [14,33,34], kinaesthetic MI is expected to exert a larger effect than visual MI on sensorimotor excitability. However, it is still unclear whether visual MI in the 1st person perspective exerts a stronger effect on somatosensory excitability than visual MI in the 3rd person perspective (perspective effect), and whether visual MI (irrespective of the perspective) exerts an effect that differs from static imagery (movement or motor effect). The present study attempts to clarify these questions by examining somatosensory excitability during different experimental conditions involving perspective, modality and motor and non-motor imagery. Our main question was: does the emphasis on one perspective or one modality affects the involvement of the somatosensory cortex during motor imagery?

Numerous studies have shown that movement execution, movement imagery, and even movement observation can decrease the somatosensory response to peripheral stimuli. Somatosensory gating has been defined as this decreased somatosensory excitability (for reviews, see [3,4]). In addition, recent advances in electroencephalographic (EEG) methods allow fast determination of somatosensory excitability by means of steady-state somatosensory evoked potentials [12,23,35]. The idea is thus to record the EEG response to a continuous train of stimuli so as to assess the excitability to somatosensory stimuli while subjects are submitted to one of a series of conditions designed to separate perspective from modality and motor from non-motor imagery. We hypothesized that the MI condition inducing the largest modulation in the steady-state response would represent a condition closest to physical movement. Moreover, because faster movements are known to cause a larger decrease in the somatosensory response, a phenomenon called *gating* [1,3,28], then, a correlation between the somatosensory gating effect and movement speed would strongly suggest the involvement of motor related processes.

Seventeen, healthy subjects (aged 21–65 years, 8 males, 4 left-handed) participated in this study. They all provided their informed consent and the project was approved by the local ethics committee. Prior to the EEG experiment the ability to imagine was assessed using two approaches: mental chronometry and the Kinaesthetic and Visual Imagery Questionnaire (KVIQ). Detailed procedures and demonstration of test–retest reliability can be found elsewhere [19,20].

Chronometric testing involved hand opening/closing movements. Although no directive was given about imagination speed, the subjects were aware that it was recorded as they were instructed to verbally signal the end of each cycle of movement and to avoid counting. The first chronometric test (screening) involved only imagined movements wherein the number of imagined movements is expected to increase with longer recording periods (15, 25 and 45 s; order randomized and counterbalanced across subjects). In the second (main) chronometric test, subjects successively imagined and physically performed five cycles of movements. Both sides were tested twice in alternation (order of side and condition were counterbalanced across subjects).

The KVIQ is a standardized questionnaire developed to assess the vividness of MI. It includes 10 gestures representing simple movements of the head, shoulders, trunk, upper limbs and lower limbs and uses a 5-point scale to rate the clarity of the image (visual subscale) and the intensity of the sensations (kinaesthetic subscale) in the 1st person perspective. A score of 5 corresponds to the highest level of imagery and a score of 1 to the lowest. Testing procedures have been described elsewhere [19,21].

During the EEG experiment, subjects were comfortably seated with their hand positioned in a custom-made adjustable armrest, eyes closed. The subjects were verbally instructed either to: (1) perform a physical movement (hand opening/closing); (2–4) imagine performing the same movement using (2) 1st person kinaesthetic motor imagery (KMI); (3) 1st person visual motor imagery (VMI_1st); (4) 3rd person visual motor imagery (VMI_3rd); or (5) imagine a static image of the front of their own house (SI). This last condition was chosen to control for attentional factors unrelated to motor imagery. In addition, this choice allowed a more direct comparison with Stinear et al. [34] who addressed similar questions (using TMS over the motor cortex to investigate changes in corticospinal excitability) using the same control condition (SI). Practice trials were performed for each condition prior to the experiment to ensure that subjects understood the tasks properly.

Throughout each block of trials, a repetitive electrical stimulation was applied to the radial nerve at 25 Hz, a frequency chosen to evoke the largest steady-state response [32]. Each trial started by: (a) one of the five verbal instructions, to indicate the task to perform; (b) a series of 10 beeps (1000 Hz pure tone, 200 ms long), both to indicate when to begin and to set the speed at which to perform the task (one beep every 3 s); (c) three beeps (same characteristics as for (b)) in rapid succession, to indicate to the subjects to stop and wait 3 s for the next verbal instruction. Notice that during condition 5 the participants were instructed to maintain the same image throughout the duration of the trial, whereas for condition 1–4 subjects had to synchronize the movements with the beeps. The order of conditions was randomized and counterbalanced across blocks and subjects. Each subject performed 8 experimental blocks (400 trials in total) separated by rest periods. The tested hand was changed after four blocks. The order of testing (dominant or non dominant first) was randomized and counterbalanced across subjects.

Assessment of the somatosensory excitability was obtained by recording the EEG response to the repetitive train of squared pulse stimuli (0.1 ms duration, 25 Hz) which was applied over the radial nerve at wrist level of the tested arm in a bipolar configuration. Electrical stimulation was performed using a Grass S88 stimulator, an isolation box (SIU5) and a constant current unit (CCU1). Intensity was individually adjusted to comfortable level (1.5 × the radiating threshold, i.e. the lowest stimulation intensity required to evoke a clear paresthesia radiating throughout the innervation territory of the nerve [36]). The EEGs were recorded at a 500 Hz sampling rate using a 128-electrodes sensor net (Electrical Geodesics Incorporated, Eugene, OR, USA) and analysed using ELAN-Pack (INSERM U821, Bron, France) and custom programs running on MATLAB software (version 6.5; MathWorks, Natick, MA). Pre-processing included automatic rejection on predefined criteria (>200 μV within 200 ms or >50 μV within 10 ms) and visual inspection. In addition, electromyographic activity (EMG) was recorded from the flexor digitorum superficialis (FDS) and the extensor carpi ulnaris (ECU) using bipolar configurations (reference electrode over the head of the olecranon). The EMG recordings were monitored to ensure that no voluntary muscle contraction occurred except when physical movements were required (condition 1). Visual inspection confirmed that no detectable muscle contraction occurred during the imagery conditions (conditions 2–5) and the waiting period between conditions (see (c) above and analyses below: this period was used for normalisation purpose).

EEG recordings were analysed using the physical execution (PE) period minus the waiting period (WP) both to localise (for each subject) the best site to record a gating effect and to normalize the data. First, the potentials evoked by the electrical stimulations during these two periods were computed for each electrode pair, and the result was rectified and averaged. This provided an index of the somatosensory excitability. Second, the amplitude of this index during movement execution was subtracted from the one corresponding to the waiting period (WP-PE). This provided an index of the somatosensory gating. Third, the electrode pair exhibiting the

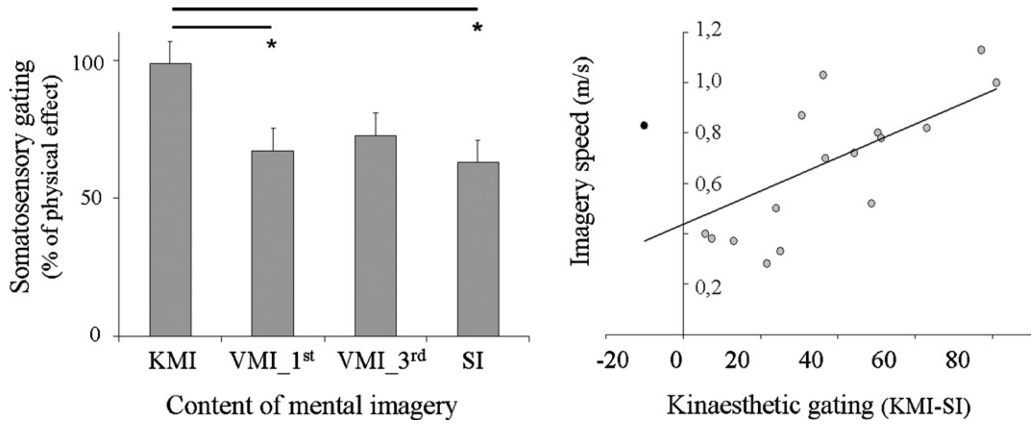

Fig. 1. (A) Gating of the somatosensory response varies with the content of mental imagery (error bar: SEM). KMI: 1st person kinaesthetic motor imagery; VMI_1st: 1st person visual motor imagery; VMI_3rd: 3rd person visual motor imagery; SI: static non motor imagery. KMI was significantly higher than VMI_1st and SI (*$p < 0.05$, Bonferroni corrected). (B) The gating effect specific to kinaesthetic imagery (KMI-SI) correlates with the self-selected speed of motor imagery. The correlation is significant ($p < 0.01$, $r^2 = 0.42$) despite a single outlier (black circle) without which the r^2 reached 0.78.

largest gating effect during movement execution was selected for further analysis of the imagery conditions. Consistent with previous studies [25,32,35], the largest responses were found contralateral to the stimulated site using electrodes pairs close to the F3-P3 and F4-P4 pairs of the 10/20 coordinate system. Fourth and finally, the output corresponding to each imagery condition (I) was normalized by means of this equation: $100 \times (\text{WP-I})/(\text{WP-PE})$. Using this procedure 0 corresponds to no gating effect while 100 corresponds to a gating effect as large as when a subject actually performs a movement. In other words, the gating effect of the imagery conditions was expressed as a percentage of the gating effect induced by physically performing a movement.

Results from the screening chronometric test showed a linear association between the number of imagined movements and the duration of the imagination period (for all subjects: $p < 0.003$, $r^2 > 0.91$), a first indication that subjects experienced expected responses in their ability to imagine a motor movement. During the main chronometric test, the self-selected speed for performing a physical movement (mean: 0.63 movement/s; SD: 0.25; range: 0.27–1.08) was highly correlated ($p < 0.0001$, $r^2 = 0.96$) to the self-selected speed for imagining the same movement (0.67 movement/s; SD: 0.27; range: 0.28–1.13). This strong relationship also holds with the self-selected speed of MI computed from the screening test ($p < 0.0001$, $r^2 = 0.89$). As the screening test involving only imagination was performed in first place, this correlation could hardly be accounted for by a memory effect from physically performing the movement. On the contrary, this reinforces the suggestion, consistent with the literature [6,8,10], that the self-selected speed of MI indicates the ease by which the motor processes are recruited. Note that the speed set in the EEG session (0.33 movement/s) was close to the lowest self-selected speed among subjects. This ensured that all subjects were able to practice MI fast enough for the needs of the experiment.

Results of the MI vividness questionnaires indicated that the visual imagery scores were larger than the kinaesthetic imagery scores (3.7 ± 0.5 SD versus 2.9 ± 0.8 SD; five point scale; $t(16) = 4.137$; $p < 0.001$). No significant effect was found for the lower versus upper limbs and for the dominant versus non dominant hand. This pattern of results is in line with previous published results [21,22] in which mean scores for three control groups (including 32, 27 and 35 individuals) were 3.7 ± 0.8 SD and 3.2 ± 0.8 SD for visual and kinaesthetic questionnaires, respectively. The similarity with present results suggests that the subjects in the present study did not experience unusual difficulty in imagining motor movements.

The gating effect associated with each of the four experimental conditions of interest (KMI, VMI_1st, VMI_3rd and SI) was tested using a repeated measure ANOVA followed by post hoc tests. Results indicated that the content of mental imagery impacts the somatosensory cortical excitability ($F(3,48) = 4.318$; partial eta square = 0.213; observed power = 0.838; $p < 0.01$; see Fig. 1A). Post hoc analysis indicated that the gating effect associated with KMI was significantly larger ($p < 0.05$, Bonferroni corrected) than the effect evoked by VMI_1st as well as that evoked by SI. Likewise, there was a trend for KMI versus VMI_3rd, although not significant when using the Bonferroni correction ($p < 0.05$, uncorrected). On the contrary, no significant difference was found between the three visual MIs (VMI_1st, VMI_3rd, SI).

One may notice from Fig. 1A that all the visual imagery conditions impact the cortical excitability at roughly half the effect of KMI (mean percentage of physical effect ± SD: KMI = 98 ± 43; FPVMI = 67 ± 37; TPVMI = 72 ± 37; SI = 63 ± 44). This suggests that a portion of the gating effect observed during MI might be related to nonspecific factors, such as attention. Indeed, attention has been found to modulate the steady-state somatosensory excitability [12], up to a point it is considered a suitable signal for brain computer interface [23]. To capture the specific contribution of KMI, the effect of SI was subtracted, separately for each subject (KMI-SI). This provided an index of the specific kinaesthetic effect regarding the involvement of the sensorimotor system. Notice that this index should not be viewed as the motor contribution to KMI given that the VMIs did not differentiate from SI. Thus, KMI-SI should be viewed as the effect of KMI minus the effect of any process related to mental imagery at large. When this index was correlated to the chronometric outcomes, a striking association appeared.

Fig. 1B demonstrates the significant correlation ($p < 0.01$, $r^2 = 0.42$) between the specific kinaesthetic effect (KMI-SI) and the self-selected speed of imagined movement during the (main) chronometric test: the faster one chooses to perform the movements during the chronometric test prior to the EEG experiment, the larger the kinaesthetic gating. Note that this correlation remains significant despite the presence of a single outlier who did not demonstrate a kinaesthetic effect larger than that for static imagery. When this outlier was removed the r^2 reached 0.78. As can be predicted from the results of the chronometric tests, the correlation also holds when considering the self-selected speed for physically performing a movement rather than imagining it ($p < 0.01$, $r^2 = 0.37$). Both correlations reinforce the interpretation that the kinaesthetic content of MI impacts the ease by which the motor system is recruited.

To the contrary, no significant association was found between the gating effect and the KVIQ scores (neither for visual and kinaesthetic subscales nor summed scores), and the low r^2 (<0.14) could not be attributed to outliers. This might be explained by the small inter-subject variability in the questionnaires, so that no firm conclusion can be drawn at present regarding this absence of correlation.

To our knowledge, this is the first study scrutinizing the impact of modality and perspective on the somatosensory excitability during mental practice. The novelty is threefold: first, we examined the somatosensory excitability; second, we examined both perspective and sensory modality within a single experiment; and third, we revealed a significant correlation of kinaesthetic effects with the speed to imagine and perform a movement.

Several previous studies have provided evidence that kinaesthesia [14,33,34] and first-person perspective [16,18] modulates motor cortex activation. Our results extend the finding to the somatosensory excitability and clarify the relationship between these two dimensions. Namely, our results support that it is the kinaesthetic dimension which leads to the maximal involvement of the somatosensory system during MI.

Present results also indicate that, irrespective of the perspective taken, the effect of visual MIs is within the same range of non motor imagery (SI). This is a surprising finding given that previous studies have demonstrated that visual mental imagery is not confounded with attention [29,30], and that other studies have found differences between the 1st and the 3rd person perspective [16,18]. Given the limited sample size ($n = 17$) one cannot exclude the fact that we may have insufficient statistical power to detect the effect of visual MIs if this effect is smaller than that of KMI. However, the statistical power was above 0.83, and enough to sort out the kinaesthetic condition. Instead, we suggest that the present lack of difference between the two perspectives might be explained by the instruction provided to the subjects. Namely, testing both perspective and modality at the same time may have prompted the subjects to better separate the kinaesthetic dimension from the 1st perspective visual MI. In previous studies looking only at either perspective or modality but not both at the same time, the subjects may have spontaneously relied (at least in part) on kinaesthetic imagery when the 1st person perspective was taken.

Finally, we demonstrate a striking association between the speed taken to imagine and perform a movement. In our view, this indicates that the modulation of somatosensory excitability is at least partially associated with motor cortex involvement. Indeed, our experimental choice to assess the cortical response evoked by peripheral stimulation allows monitoring not only the somatosensory system, but the motor system as well through the gating effects, i.e. the fact that involving the motor system decreases the somatosensory excitability [1,3,4,28]. Thus, one should question whether the present effects tell more about the somatosensory system or both the motor and somatosensory system. Here results of chronometric tests give an important insight: as a close association was found between the gating effects specific to the kinaesthetic imagery on the one hand and the time to perform and imagine a movement on the other hand, it seems reasonable to suggest that the motor system was involved together with the somatosensory system. Thus, the effect of focusing on the kinaesthetic aspects while practicing motor imagery should be interpreted as a response of the sensorimotor system as a whole rather than the somatosensory system exclusively. This interpretation is in line with a growing body of evidence for a centrally generated sense of effort relating kinaesthesia with the motor system [11,27,31]. For practical purposes however, and although the present study stresses the importance of the kinaesthetic aspects to mental practice, it is not enough to completely lay aside visual MI. Given the unfamiliarity of most people with kinaesthetic imagery, the best strategy could be to first orient the trainee to a 1st person perspective using visual cues, then to maximise the kinaesthetic content of this 1st person imagery.

The results of the present study indicate that kinaesthetic motor imagery modulates the processing of somatosensory information and supports the view that the kinaesthetic content of motor imagery is a key factor to maximize its impact on the sensorimotor system.

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