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ORIGINAL ARTICLE

Imagining handwriting movements in a usual or unusual position: effect of posture congruency on visual and kinesthetic motor imagery

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Abstract

Motor imagery has been used in training programs to improve the performance of motor skills. Handwriting movement may benefit from motor imagery training. To optimize the efficacy of this kind of training, it is important to identify the factors that facilitate the motor imagery process for handwriting movements. Several studies have shown that motor imagery is more easily achieved when there is maximum compatibility between the actual posture and the imagined movement. We, therefore, examined the effect of posture congruency on visual and kinesthetic motor imagery for handwriting movements. Adult participants had to write and imagine writing a sentence by focusing on the evocation of either the kinesthetic or visual consequences of the motion. Half the participants performed the motor imagery task in a congruent posture (sitting with a hand ready for writing), and half in an incongruent one (standing with arms crossed behind the back and fingers spread wide). The temporal similarity between actual and imagined movement times and the vividness of the motor imagery were evaluated. Results revealed that temporal similarity was stronger in the congruent posture condition than in the incongruent one. Furthermore, in the incongruent posture condition, participants reported greater difficulty forming a precise kinesthetic motor image of themselves writing than a visual image, whereas no difference was observed in the congruent posture condition. Taken together, our results show that postural information is taken into account during the mental simulation of handwriting movements. The implications of these findings for guiding the design of motor imagery training are discussed.

Introduction

Motor imagery (MI) is defined as the ability to mentally rehearse a specific motor action without any corresponding overt motor output (Decety, 1996; Jeannerod, 1994, 1995). According to Jeannerod (1995), MI and motor preparation share a common system of motor representations. This ability can be viewed as an embodied cognitive process, involving the simulation of one's own body movements (de Lange, Helmich, & Toni 2006; Hanakawa, 2016). According to embodied cognition theories, cognitive processes such as imagery are grounded in our bodily interactions with the environment (Barsalou, 2008). These theories focus on the role of simulation in cognition (Borghi & Cimatti, 2010). According to Jeannerod (2001, 2006), during MI, the motor system is covertly activated via a neural simulation process. This simulation process is embodied, not only because it occurs at a neural level, but also because it constitutes a form of prediction that is used during the motor preparation of action and to understand the action of other people (Iachini, 2011; Pezzulo, 2011).

Numerous neuroimaging studies have supported the hypothesis of motor simulation, revealing the involvement of similar neural structures, including the parietal and prefrontal cortices, supplementary motor area, premotor and primary motor cortices, basal ganglia, and cerebellum, during both the imagination and execution of movements (e.g., Decety, 1996; Fadiga & Craighero, 2004; Gerardin et al., 2000; Hétu et al., 2013; Jeannerod, 2001; Jiang, Edwards, Mullins, & Callow, 2015; Ridderinkhof & Brass, 2015; Zhang et al., 2016). Although MI and motor execution have overlapping networks, a number of cortico-subcortical

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regions are more specifically engaged in MI (Gerardin et al., 2000), highlighting differences between these two states. There is also physiological and behavioral evidence for resemblances between imagined and actual movements, as research has highlighted (1) similar autonomic responses during MI and preparation (Decety, Jeannerod, Durozard, & Baverel, 1993; Decety, Jeannerod, Germain, & Pastene, 1991), and (2) a correspondence between the durations of executed and imagined movements (e.g., Decety, Jeannerod, & Prablanc, 1989; Decety & Michel, 1989; for a review, see Guillot & Collet, 2005). Taken together, these results strongly suggest that overt and covert actions share similar mechanisms of motor control.

It has been argued that MI is based on the ability to generate forward and inverse internal models for movement control (Wolpert & Flanagan, 2001). The forward model predicts the sensory consequences of movement, based on the actual state of the motor system (e.g., the biomechanical properties of the relevant effector system) and motor commands. The inverse model performs the opposite transformation, in that it specifies the motor commands that will cause the desired movement. During the execution of the movement, the sensory prediction generated by the forward model is compared with actual feedback, to detect any errors. During MI, the execution of motor commands issued by the inverse model is actively blocked, but the forward model still predicts the sensory consequences of the movement, based on a copy of the motor commands (Blakemore & Sirigu, 2003; Grush, 2004; Imamizu & Kawato, 2009; Kilteni, Andersson, Houborg, & Ehrsson, 2018; Wolpert & Flanagan, 2001). Consequently, MI could be viewed as an internal dynamic state, during which individuals use internal models to consciously predict the sensory consequences of an action (Gabbard, Caçola, & Bobbio, 2011; Grush, 2004; Papaxanthis, Pozzo, Skoura, & Schieppati, 2002).

As MI involves the simulation of one's bodily movements, this ability necessarily relies on the body schema, which combines visual and proprioceptive information into a unified internal representation of the body in the mind (Assaiante, Barlaam, Cignetti, & Vaugoyeau, 2014; Fourkas, Ionta, & Aglioti, 2006). Imagining the position of body parts in space thus involves two main sources of sensory information: vision and proprioception (Shenton, Schwoebel, & Coslett, 2004). These sensory modalities can be concomitantly used during the imagery process and weighted differently according to participants' preferences for a particular imagery modality or the specific imagery instructions that are given to them (Munzert & Lorey, 2013; Munzert, Lorey and Zentgraf 2009). These imagery instructions may indicate which sensory modality to use and encourage adults to focus either on the evocation of the action's kinesthetic or on visual consequences. MI based on proprioceptive information (kinesthetic MI) involves feeling oneself performing an action, whereas MI based on visual information (visual MI) involves visualizing the spatial coordinates of the motion from a first- (internal MI) or third- (external MI) person perspective. Individuals adopting the first-person perspective explicitly form a representation of themselves in action by visualizing the consequences of the movement-to-imagine from an internal point of view. By contrast, individuals adopting the third-person perspective form a visual representation of themselves from an external viewpoint, as if they were a spectator. Neuroimaging studies have revealed that brain activation differs according to the type (visual or kinesthetic) of imagery (Guillot et al., 2009; Milton, Small, & Solodkin, 2008; Toussaint & Blandin, 2010).

Owing to the similarity between executed and imagined movements, many investigators have suggested using MI in training programs (also called mental practice) to complement the physical practice, either to improve motor skill acquisition (Feltz & Lander, 1983; Jeannerod, 2001) or to aid motor recovery after damage to the central nervous system (Jackson et al., 2001). Mental practice is a training method whereby the internal reproduction of a given movement is extensively repeated, with the intention of improving motor performance (Jackson et al., 2001). There is converging evidence from behavioral and neuroimaging studies that mental practice has positive effects on motor performance and learning (e.g., Adams et al., 2017; Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004; for a review, see Schuster et al., 2011). To optimize the efficacy of this kind of training, it is important to identify the factors that may facilitate the MI process. Interestingly, various studies have revealed an influence of sensory inputs on the MI process (e.g., Guilbert, Jouen, & Molina, 2018; Guilbert, Molina, & Jouen, 2016; Mizuguchi, Nakata, Uchida, & Kanosue, 2012; Naito et al., 2002; Parsons, 1994; Sakamoto, Muraoka, Mizuguchi, & Kanosue, 2009; Sirigu & Duhamel, 2001; Stevens, 2005; Vargas et al., 2004). For instance, MI is more easily achieved when the actual posture and imagined movement are congruent (Ionta, Fourkas, Fiorio, & Aglioti 2007; Parsons, 1994; Saimpont, Malouin, Tousignant, & Jackson 2012; Sirigu & Duhamel, 2001; Vargas et al., 2004). Based on a mental chronometry paradigm, some of these studies have compared real and mental durations under congruent or incongruent posture conditions (Saimpont et al., 2012; Vargas et al., 2004). Results have revealed closer matching between actual and mental durations when postural information is congruent with the imagined movement than when it is incongruent. For example, Vargas et al. (2004) found a higher degree of correlation between overt and covert movement times when participants were instructed to imagine finger movements while maintaining their own hand in a congruent versus incongruent posture. Likewise, Saimpont et al. (2012) observed that imagined walking times were closer to actual walking times when participants were instructed to perform the MI task in a ready-for-walking position, rather than a sitting position. These findings have been confirmed by studies using the transcranial magnetic stimulation technique to demonstrate that corticospinal excitability during MI is enhanced when postural information is closed to that present during the actual execution of the movement, while an incongruent posture produces the reverse effect (Fourkas et al., 2006; Mizuguchi et al., 2012; Vargas et al., 2004). This facilitating effect of posture congruency seems to depend on the imagery modality (Fourkas et al., 2006). Posture affects corticospinal excitability more when participants mentally simulate the kinesthetic versus visual consequences of the motion, indicating that first-person kinesthetic MI is a more embodied cognitive process than first-person visual MI. Taken together, these findings suggest that the MI process can be facilitated when postural information is congruent with the movement-to-imagine.

To date, the influence of posture on MI performance has been studied for rotational hand movements (Parson, 1994; Sirigu & Duhamel, 2001), repetitive finger movements (Fourkas et al., 2006; Vargas et al., 2004), or walking movements (Saimpont et al., 2012), but never for handwriting movements, even though the latter could be trained or rehabilitated with mental practice. For instance, a very recent study found that the handwriting quality of children with dysgraphia improved after 12 MI training sessions (Puyjarinet, 2019). Therefore, the question remains as to whether the congruency of posture may also facilitate the mental simulation of handwriting movements.

Handwriting is a complex activity that requires the coordination of different joints (proximal and distal) and postural adjustments to maintain an upright posture against gravity (Erhardt & Meade, 2005). Movements enabling the actual formation of letter shapes and their spatial arrangement on the page depend on afferent information provided by both visual and proprioceptive systems (for a review, see Danna & Velay, 2015). More specifically, the spatial characteristics of the written trace are mainly guided by vision whereas proprioception informs individuals about the kinematics and dynamics of their handwriting movements. Consequently, handwriting tasks have both visuospatial and proprioceptive components, and should in theory be equally associated with visual and kinesthetic MI. To our knowledge, only two studies have explored MI in a situation based on a handwriting task (Decety & Michel, 1989; Papaxanthis et al., 2002). The results of these studies revealed that the time taken to imagine writing a sentence (Decety & Michel, 1989) or an address (Papaxanthis et al., 2002) is very similar to the time taken to produce the actual writing gesture. These findings suggest that both real and imagined handwriting movements are governed by the same motor representation. In these two studies, adult participants were asked to feel themselves making the gesture during imagined writing trials. Consequently, these two studies focused solely on kinesthetic MI and did not explore visual MI for handwriting movements.

The present study examined the effect of body configuration on first-person (i.e., internal) visual and kinesthetic MI for handwriting movements. More specifically, our aim was to investigate whether postural information is integrated into kinesthetic and visual imagery of handwriting movements. In the present experiment, MI performances were evaluated using a mental chronometry paradigm in a situation based on a handwriting task. Participants were instructed to write and to imagine writing a sentence by focusing on the evocation of the action's kinesthetic or visual consequences. The evaluation of the temporal features of the imagined or executed movement was complemented by self-report ratings of MI vividness. Several studies have demonstrated that these two measures of imagery are unrelated and therefore do not tap into the same dimensions of the MI process (Saimpont, Malouin, Tousignant, & Jackson 2015; Williams, Guillot, Rienzo, & Cumming, 2015). Consequently, combining these measures should yield a more accurate representation of participants' imagery capacity.

To evaluate the influence of body configuration, we compared MI performances when participants performed the task in a congruent (sitting with hand-ready-for-writing) versus incongruent (standing with arms crossed behind the back and fingers spread wide) posture. As MI has similar mechanisms to those used in motor control, we predicted that MI performance would be influenced by participants' actual posture. More specifically, and in line with the literature, we expected MI performances to be better when postural information was congruent with the handwriting movement than when it was incongruent, especially when participants simulated the proprioceptive consequences of the movement.

Methods

Participants

Students at Paris 8 University enrolled on the first year of a psychology degree were all given the opportunity to participate in the present study. A total of 56 participants (43 women and 13 men; mean age = 24.25 years, SD = 8.75) volunteered to take part in the experiment. After signing an informed consent form, they were randomly assigned to either the congruent posture group ($n = 28$; 23 women, mean age = 23.29 years, SD = 9.68; 5 men, mean age = 25.13 years, SD = 5.34) or the incongruent posture group ($n = 28$; 20 women, mean age = 23.78 years, SD = SD = 8.7; 8 men, mean age = 27.43 years, SD = 8.17). To check that participants in the two groups had a similar ability to engage in first-person kinesthetic and visual MI, we administered the short version of the Kinesthetic and Visual Imagery Questionnaire (KVIQ-10; Malouin et al. 2007). No significant difference was observed between the two groups (congruent vs. incongruent posture) when we compared scores on the kinesthetic imagery (Ik) scale, $t(54)=1.106$, $p=0.274$, and visual imagery (Iv) scale, $t(54)=0.108$, $p=0.914$. Finally, participants were naive to the purpose of the study and were only debriefed at the end of the session.

Imagery questionnaire

First-person kinesthetic and visual MI was evaluated by means of the KVIQ-10 (Malouin et al. 2007). This questionnaire is designed to determine the extent to which individuals are able to mentally simulate different movements (e.g., forward shoulder flexion, hip abduction, or foot-tapping) from a first-person perspective after physically performing the required action. The questionnaire includes 10 items: five movements for the Ik scale, and five movements for the Iv scale. Participants were asked to rate the clarity of the visual images or intensity of the sensations associated with the imagined action on a 5-point scale ranging from 1 (no image/no sensation) to 5 (image as clear as seeing/sensation as intense as executing the movement).

Experimental task

In this experiment, MI performances for handwriting movements were assessed using a mental chronometry paradigm in a situation based on the handwriting task initially designed by Decety and Michel (1989). Participants had to write and imagine writing the opening sentence of a well-known French fable ("Maître corbeau sur un arbre perché, Tenait en son bec un fromage") on two lines. All participants stated that they knew this sentence. During the imagined writing trials, participants were instructed to close their eyes and imagine writing the sentence from a first-person perspective (i.e., as if they were executing the handwriting movement), at their normal speed and without executing any actual movement. In half the cases (Iv trials), they had to focus on the visual consequences of the movement (seeing their own handwriting the sentence from an internal and not external view). In the other half (Ik trials), participants were asked to focus on the kinesthetic consequences of the movement (feeling their hand in action). During the actual writing trials, participants were instructed to physically write the sentence at their normal speed. To ensure that data collection was identical across the two movement conditions, participants were instructed to say "Go" once they had started imagining writing (imagined writing condition) or when they had actually started writing (actual writing condition). They had to say "Stop" once they had stopped imagining writing (imagined writing condition) or had actually finished writing (actual writing condition). No instructions about imagined or actual movement duration were given to participants. Each participant performed the experiment in three handwriting conditions: Iv, Ik, and executed (E).

Procedure

The experiment took place in a quiet room. After providing their informed consent, participants completed the KVIQ-10 (Malouin et al., 2007). The experimenter then explained the handwriting task to participants, who were allowed to read the well-known sentence printed on a sheet of paper. This sheet was removed before the start of the experimental task.

Participants performed three blocks of five trials: Iv block, Ik block, and E block. Each block began with a training trial to familiarize participants with the condition. Participants, therefore, performed a total of 15 trials (5 trials in Iv block, 5 trials in Ik block, and 5 trials in E block). In the E block, participants actually wrote the sentence out five times in succession. Repeating the executed trials before the imagery trials could have resulted in the formation of traces in short-term motor memory, thus affecting MI performances. To avoid this potentially undesirable effect of motor memory on imagined movement duration, the two imagery blocks (Iv and Ik) were performed first, in a counterbalanced order (half the participants began with the Iv block, and a half with the Ik block), and the E block was always performed last (see Fig. 1).

To evaluate MI vividness, after each imagined writing trial, participants rated either the clarity of their images (visual trials) or the intensity of their sensations (kinesthetic trials) on a 5-point scale identical to that used for the KVIQ-10.

Half the participants ($n=28$) performed the two imagery blocks (visual and kinesthetic) in a congruent posture, while the other half ($n=28$) performed them in an incongruent posture. Participants in the congruent posture group were seated in a chair with their forearm, wrist, and hand resting on a table as if they were preparing to write. Participants in the incongruent posture group stood with their arms crossed behind their back and fingers spread wide.

Data analysis

Assessment of temporal features of movement

We used a mental chronometry paradigm to evaluate MI capacity. More specifically, the similarity between the durations of executed versus (visually or kinesthetically) imagined movements was taken as an indicator of participants' ability to internally simulate handwriting movements. Imagined and executed movement durations were assessed

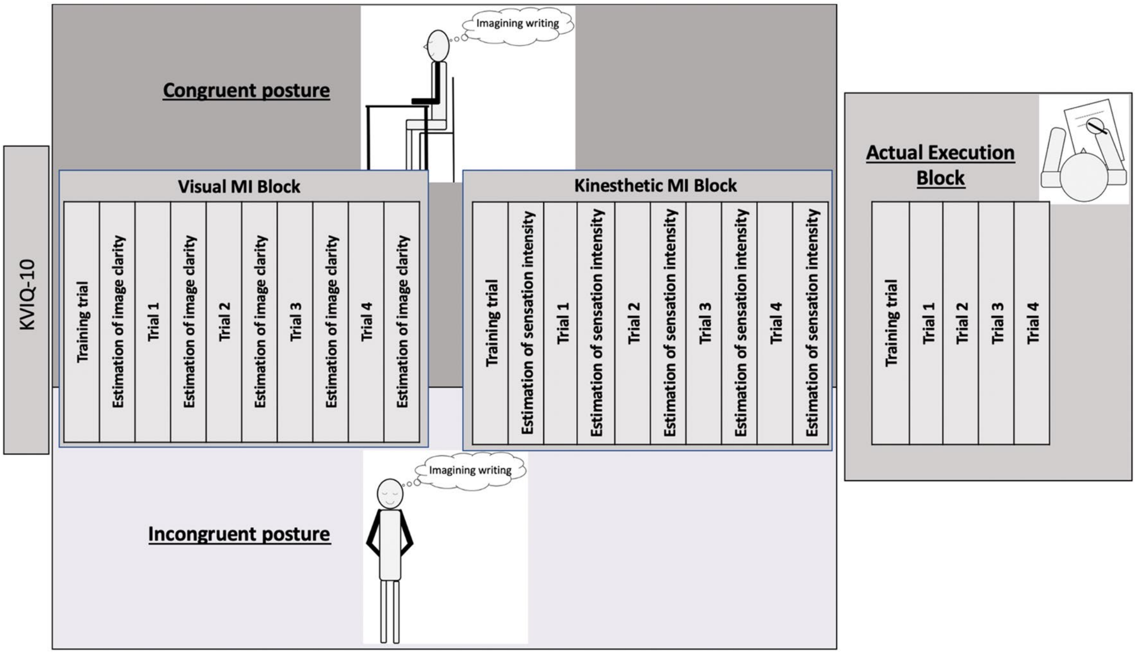

Fig. 1 Experimental protocol for the congruent posture (top) and incongruent posture (bottom) groups. The order of presentation of the visual MI and kinesthetic MI blocks was counterbalanced across participants

in each trial, apart from the first training trial of each block. We recorded movement durations for 12 trials (4 Iv trials, 4 Ik trials, and 4 E trials). In the three handwriting conditions (Iv, Ik, and E), the experimenter used an electronic stopwatch to record the time interval between participants' go and stop signals.

For temporal similarity, we averaged the movement times of each participant across the four experimental trials in each of the three handwriting conditions (Iv, Ik and E). To evaluate the temporal correspondence between the imagined and actual handwriting movements, we calculated two performance indices (see Skoura, Vinter, & Papaxanthis, 2009) for each participant: one to assess the temporal correspondence between the visually imagined and actual movement durations (PI_{visual}), and one to measure the temporal correspondence between the kinesthetically imagined and actual movement durations ($PI_{kinesthetic}$). We applied the same calculation as in Skoura et al. (2009). The absolute difference ($|E - I|$) between the mean durations of executed versus imagined (either visual or kinesthetic) handwriting movements were calculated. To account for interindividual differences in movement duration, the absolute difference $|E - \mathrm{I}|$ was divided by the mean executed movement time, multiplied by 100 ($(|E - I|/E) \times 100$), for each participant. The closer the PI was to zero, the stronger the temporal correspondence between the executed and imagined movements. A repeated-measures analysis of variance (ANOVA), with posture (congruent/incongruent) and order of imagery blocks (visual followed by kinesthetic/kinesthetic followed by visual) as between-participants factors, and MI modality (visual/kinesthetic) as a within-participants factor, was conducted to determine whether the temporal correspondence between the imagined and executed movements (PIs) varied within each condition.

The assessment of temporal similarity was complemented by an evaluation of within-participant movement duration variability for each condition, to explore whether the actual and imagined movement durations remained stable across trials. For this purpose, we calculated a coefficient of variation for each participant, corresponding to the ratio between the standard deviation and mean handwriting duration, multiplied by 100. The closer the coefficient was to zero, the lower the variability of movement durations across the trials. We calculated three coefficients of variation for each participant: one for executed movement times (CV_E), one for visually imagined movement durations (CV_{Iv}), and one for kinesthetically imagined movement durations (CV_{Ik}). A repeated-measures ANOVA, with posture (congruent/incongruent) and order of imagery blocks as between-participants factors, and handwriting condition (Iv/Ik/E) as a within-participants factor, was conducted to determine whether movement duration variability (CV) varied within each condition.

Assessment of MI vividness

A vividness score was calculated for each MI condition (visual and kinesthetic). The clarity of images (after each Iv trial) and intensity of sensations (after each Ik trial) ratings were averaged for each participant. These mean scores could vary from 1 to 5. A repeated-measures ANOVA, with posture (congruent/incongruent) and order of imagery blocks as between-participants factors, and MI modality (visual/kinesthetic) as a within-participants factor, was conducted to determine whether MI vividness (mean clarity of images and intensity of sensations scores) varied within each condition.

Relationship between MI vividness scores and performance indices

To determine whether performance indices were related to MI vividness scores, we calculated correlations for each group (congruent vs. incongruent posture) and each imagery modality (visual and kinesthetic).

Results

As we did not detect any significant effect of the order of imagery blocks on the measures (PIs, CVs, and vividness scores), this factor was removed from the analyses. Expected interactions were analyzed using planned comparisons.

Temporal features of movement durations

Assessment of temporal correspondence: analysis of performance indices

As we can see in Fig. 2, the ANOVA revealed a significant effect of posture congruency, $F(4, 224) = 4.6$, $p = 0.037$, $\eta^2 = 0.08$, such that PIs were significantly closer to zero when participants imagined a writing movement in a congruent posture (M = 28.50, SD = 19.59) rather than in an incongruent one (M = 38.90, SD = 22.16), whatever the MI modality (visual or kinesthetic). The interaction between posture and MI modality did not reach statistical significance, $F(1, 54) = 2.85$, $p = 0.097$.

Assessment of movement duration variability: analysis of coefficients of variation

A significant effect of handwriting condition was found, $F(2, 108) = 75.14$, $p < 0.001$, $\eta^2 = 0.39$, whereby CVs were lower for E (M = 5.18%, SD = 3.16%) than for either Iv (M = 11.13%, SD = 8.35%) or Ik (M = 13.19%, SD = 6.38%). As we can see in Fig. 3, the interaction between handwriting condition and posture was significant, $F(2, 108) = 5.64$, $p < 0.01$, $\eta 2 = 0.09$ (see Fig. 3). This expected interaction was more specifically examined by planned comparisons, which revealed that $\mathrm{CV}_{\mathrm{Ik}}$ tended to be significantly higher in the incongruent posture group (M = 14.74, SD = 6.8) than in the congruent posture group (M = 11.64, SD = 5.64), $F(1, 54) = 3.46$, $p = 0.068$. No difference was observed between the congruent and incongruent groups on either $\mathrm{CV}_{\mathrm{Iv}}$, $F(1, 54) = 2.57$, $p = 0.11$, or CV_{E}, $F(1, 54) = 0.61$, $p = 0.44$.

MI vividness: analysis of vividness score

Analysis showed a main effect of MI modality, $F(1, 54) = 12.89$, $p < 0.001$, $\eta^2 = 0.18$. Mean vividness scores were higher when participants were asked to focus on the visual consequences of handwriting (M = 3.75, SD = 0.76) than when they had to imagine the kinesthetic consequences of movement (M = 3.26, SD = 1.10). We observed a significant interaction between handwriting condition and posture, $F(1, 54) = 11.32$, $p < 0.01$, $\eta^2 = 0.17$ (Fig. 4). Planned contrasts revealed that vividness scores were higher in the congruent posture group (M = 3.57, SD = 1.07) than in the incongruent posture group (M = 2.95, SD = 1.06) when participants focused on the kinesthetic consequences of the movement,

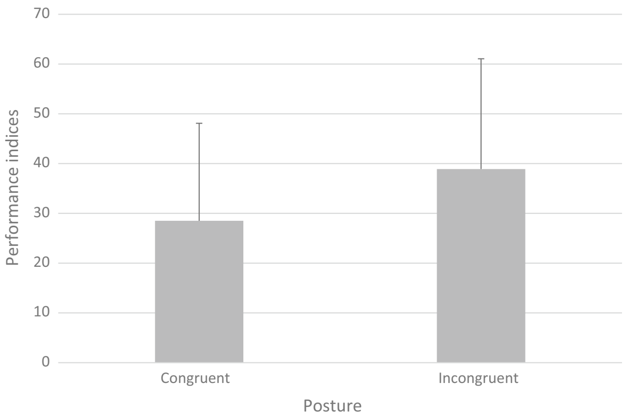

Fig. 2 Performance indices (means and standard deviations) according to posture (congruent or incongruent)

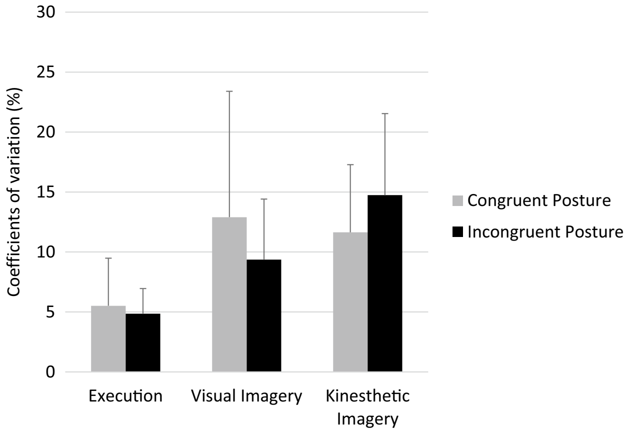

Fig. 3 Coefficient of variation (mean and standard deviation) according to posture (congruent or incongruent) and handwriting condition (execution, visual MI, and kinesthetic MI)

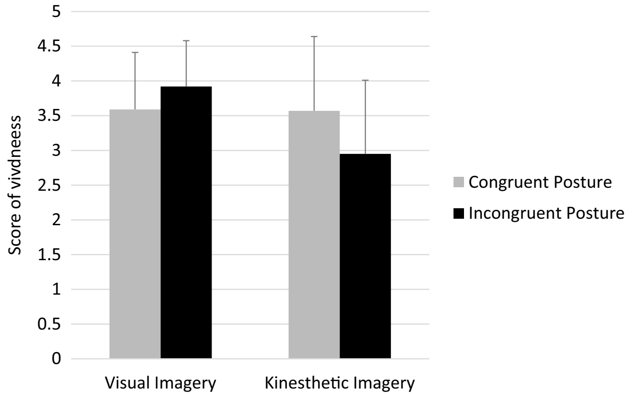

Fig. 4 Vividness score (mean and standard deviation) according to posture (congruent or incongruent) and MI modality (visual or kinesthetic)

Table 1 Correlations (*r* and *p*) between performance indices and MI vividness scores for each group (congruent vs. incongruent posture) and each imagery modality (visual and kinesthetic)

	r	*p*
Congruent posture		
Visual MI	−0.30	0.12
Kinesthetic MI	−0.15	0.45
Incongruent posture		
Visual MI	−0.27	0.16
Kinesthetic MI	−0.18	0.35

$F(1, 54) = 4.69$, $p = 0.03$. By contrast, vividness scores in the congruent posture (M = 3.59, SD = 0.82) and incongruent posture (M = 3.92, SD = 0.66) groups were comparable when participants focused on the visual consequences of the movement, $F(1, 54) = 2.76$, $p = 0.10$.

Relationship between MI vividness scores and performance indices

We calculated correlations between performance indices and MI vividness scores for each group (congruent vs. incongruent posture) and each imagery modality (visual and kinesthetic). As revealed in Table 1, no significant correlation was found. Thus, whatever the posture group and whatever the imagery modality, performance indices were not related to MI vividness scores.

Discussion

The present study was designed to examine the effect of posture congruency on visual and kinesthetic MI for the handwriting movement. To this end, we compared visual and kinesthetic MI performances (temporal features of movement and vividness) of two groups of participants. In the first group, participants were asked to imagine handwriting a sentence in a congruent posture, while in the second group, participants had to imagine the same movement in an incongruent posture. We expected MI performances to be better in the congruent posture group than in the incongruent one, especially when participants simulated the proprioceptive consequences of the movement.

Concerning the temporal features of movement, our results partially confirmed our hypothesis, as we found a higher level of similarity between the imagined and executed movement durations when participants performed the MI task in a congruent posture. Contrary to our expectation, the interaction between posture and MI modality did not reach significance for performance indices, indicating that posture had a comparable effect on the mean duration of both visual and kinesthetic imagined movements. This result suggests that the simulation of both the visual and kinesthetic consequences of handwriting movement integrates the actual bodily position. However, exploration of the variability in imagined movement durations indicated that visual MI and kinesthetic MI are not affected by posture in the same manner. In our experiment, the variability in imagined movement durations tended to increase when participants had to focus on the kinesthetic consequences of the movement while maintaining an incongruent posture.

Our results corroborate other behavioral studies showing that MI is more easily achieved when postural information resembles that present during the actual execution of the movement (Ionta et al. 2007; Parsons 1994; Saimpont et al. 2012). Neuroimaging studies have also revealed that body position influences activity in neural structures during MI (de Lange et al. 2006; Lorey et al. 2009). Greater activation in the parieto-insular region, which is associated with the integration of multisensory inputs and reafferent information processing, was observed when adult participants imagined hand movements kinesthetically in a congruent versus incongruent posture (Lorey et al., 2009). According to these authors, the higher level of activation when hand posture was congruent reflected a mechanism that facilitated the matching of the afferent signal with the sensory prediction. We can thus speculate that during MI, when actual postural information conflicts with the movement to be imagined, the prediction is less accurate and the capacity to maintain the image is diminished. More specifically, our results suggest that both kinesthetic and visual imagery are embodied phenomena arising from sensations related to the body, as revealed by the effect of posture congruency for performance indices. Visual and kinesthetic feedback is naturally used during the control of actual handwriting movements (e.g., Alamargot & Morin, 2015; Chartrel & Vinter, 2006; Danna & Velay, 2015; Guilbert, Alamargot, & Morin, 2019). As well as playing a crucial role in controlling the spatial features of the written trace (exteroceptive function of vision; Smyth & Silvers, 1987; Tamada, 1995; Van Doorn & Keuss, 1992), vision sight appears to have a second function, probably shared with the articular proprioceptive system, which concerns the accurate formation of movement sequences (proprioceptive function of vision; Alamargot, Chesnet, & Caporossi 2012; Smyth & Silvers, 1987). This may explain why, during the visual imagery of handwriting, the simulation of the visual consequences of the action was not totally dissociated from afferent information about the body's current position, even if participants were told to concentrate on the visual aspect of the movement.

As MI is a representation of the body parts' positions in space, this ability is necessarily related to the body schema. To construct the body schema, multiple modalities of sensory information (notably visual and proprioceptive) are integrated into a unified internal representation (Assaiante et al., 2014). Several studies have explored the respective contributions of these sensory modalities to the online representation of the body in space (e.g., Bremner et al., 2013; Maravita, Spence, & Driver, 2003). Adults integrate these sensory information (haptic, visual) in a statistically optimal manner, weighting each sensory modality in proportion to its relative reliability in a particular context. In the present study, participants were asked to close their eyes during imagined trials and were thus deprived of vision. Therefore, under these circumstances, proprioceptive information may have represented the dominant sensory input in the calculation of the body schema.

Overall, we noticed greater variability in the duration of imagined movements, compared with actual movements. Other studies have also shown that, compared with real movement times, imagined movement times appear less stable across trials in the same participants (Papaxanthis et al., 2002; Skoura et al., 2009). As indicated by Papaxanthis et al. (2002), the greater variability in imagined movement duration may be due to the absence of the afferent signals that are normally generated when individuals actually perform an action. During the execution of an action, peripheral feedback allows the internal models to be updated and recalibrated for the next movement. Kinesthetic feedback plays an essential role in this recalibration process. Several studies conducted in patients lacking proprioceptive input from their limbs have revealed greater variability in both the spatial organization of movement and the temporal coordination between multiple joints (Ghez & Sainburg, 1995; Sainburg, Poizner, & Ghez, 1995). These results support the view that kinesthetic information is mainly used to update the internal model in the course of a movement, and can explain the greater temporal variability of kinesthetically imagined movements compared with visually imagined or actual movements in the incongruent condition.

Posture congruency affects not only the temporal features of the imagined movement but also MI vividness. It should be noted that no correlations were found between performance indices and subjective vividness ratings. Thus, the temporal similarity between the actual and imagined movement was not related to participants' estimation of the vividness of their motor images. This result confirms that the two measures address different components of MI quality (Saimpont et al., 2015; Williams et al., 2015). In the present study, participants had greater difficulty forming a precise kinesthetic image of themselves writing when they had to cross their hands behind their back (incongruent posture) than when they were in a ready-to-write posture. As indicated by Munzert and Lorey (2013), individuals who are experienced in processing kinesthetic information have a greater ability to generate kinesthetic imagery. Accordingly, motor skill novices report greater difficulty engaging in kinesthetic MI than experts do. In the present study, imagining a movement in a different posture from that usually used may have created an unfamiliar and conflictual situation, and consequently hindered the ability to engage in the kinesthetic MI.

Taken together, our results indicate that bodily information is integrated during the imagery of handwriting movements. As MI shares motor processes with the physical execution of movement, these findings suggest that the current posture is used to predict the sensory consequences of the actual upcoming handwriting movement with a forward model. However, our study has several limitations that may temper the interpretation of our results. As recommended by several authors (Guillot & Collet, 2005; Guillot, Hoyek, Louis, & Collet, 2012; Saimpont et al., 2015; Williams et al., 2015), we assessed both the vividness and the temporal features of the imagined movement, which tap into different dimensions of MI. Although the complementarity of these measures allowed us to gain a more comprehensive view of this phenomenon, each measure has disadvantages. Concerning the vividness assessment, we used the scale of KVIQ-10 test, in which participants rate the clarity of the visual images and the intensity of the sensations associated with the kinesthetic image on a 5-point scale. However, the self-report nature of this scale may induce an interpretation bias, with participants differently interpreting the descriptors. For this reason, data collected with this scale are usually submitted to an analysis of variance (e.g., Malouin, Richards, & Durand, 2010; Malouin, Richards, Durand, & Doyon, 2008; Saimpont et al., 2012). It may well be that vividness is not best measured on a discrete scale, and that the use of a visual analog scale would be more appropriate for both assessing and analyzing vividness. Concerning the recordings of imagined movement duration, as participants in the incongruent group stood with their arms crossed behind their back and fingers spread wide, they were unable to hold a stopwatch. Imagined movement duration was therefore recorded by the experimenter, which may have reduced the accuracy of this measure. Furthermore, as indicated by Guillot et al. (2012), different factors, such as the perceived difficulty of the task and the way in which participants focused their attention during MI, may have affected the duration of the imagined movement. Future studies will have to clarify the impact of each of these factors on the temporal features of MI.

Another interesting point, which deserves further exploration, concerns electromyographic activity during MI. Several studies have revealed that the same muscles may be activated during both MI and motor execution (for a review, see Guillot, Lebon, & Collet, 2010). Two main theories have been put forward to explain this muscle activity during MI. First, central representation theory argues that MI is centrally generated, and the subliminal EMG activation may stem from incomplete motor command inhibition. Second, according to peripheral theory (or psychoneuromuscular theory), muscle activity recorded during MI may be sufficient to provide proprioceptive feedback to the central nervous system that drives the image generation process. From this perspective, we can assume that the effect of posture congruency observed in the present study resulted from different types of residual electromyographic activity in the two groups (congruent vs. incongruent). More specifically, subliminal activation of the muscles involved in handwriting may have been facilitated when the participants' hand was in a position ready for writing, rather than with the fingers spread wide. In future studies, the electromyographic activity could be assessed to determine whether the effect of posture congruency on MI is mediated by subliminal muscular activation.

Finally, we can speculate that adopting an appropriate posture may favor the prediction mechanism that precedes the execution of handwriting movements. However, more studies are needed to confirm this assumption. In the present research, the incongruent posture (standing with arms crossed behind the back and fingers spread wide) was an unusual and nonprototypical handwriting position. Further studies should be conducted to explore whether MI performances are modulated when participants have to simulate the movement in other more usual and prototypical postures.

Conclusion

To conclude, this study contributes to a better understanding of how bodily information is integrated with the simulation of handwriting in adults. Our results reveal that the simulation of handwriting movements can be facilitated when the posture is congruent with the movement-to-imagine during the MI process. The ability to engage in imagery is especially impacted by posture when participants are instructed to focus on the movement's kinesthetic consequences. In addition to providing insight into the mechanisms that underlie motor planning during handwriting, the findings of the present study could be useful for guiding MI training such as mental practice. To optimize the efficacy of this kind of training, participants could be encouraged to adopt a posture congruent with the movement-to-imagine during the MI process. Furthermore, there the question of which imagery modality (visual or kinesthetic) participants should adopt during mental practice. Visual imagery practice is not always the most relevant means of improving motor performance (e.g., Meugnot, Agbangla, Almecija, & Toussaint, 2015). Our results revealed that, in a congruent posture condition, adults can use the two imagery modalities equally well. As handwriting involves both visuospatial and fine motor control, we believe that visual and kinesthetic imagery could be used to train different aspects of handwriting by mental practice. Visual imagery seems to be better for the mental practice of motor skills that involve reproducing a form, while kinesthetic imagery is better for motor tasks that require greater motor control and acquisition of the movement's duration characteristic (Féry 2003). As mental practice can be used to learn or rehabilitate handwriting movement in children (see Puyjarinet 2019), further studies should explore whether children are able to use these two imagery modalities for handwriting movements.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in this study involving human participants were conducted in accordance with the ethical standards of the institutional and/or national review board, the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards, and France's 1988 Huriet Act on the bioethical protection of persons involved in human experimentations.

Informed consent Informed consent was obtained from all individual participants included in the study.

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