



Effects of short-term hand immobilization on anticipatory mechanism for tool use

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Abstract

The short-term immobilization of a limb such as the right arm can impair sensorimotor mechanisms, which in turn reduces motor control of this arm. However, it is not known whether immobilization also impairs the anticipatory mechanism for tool-use without actual enactment. In two experiments, we asked participants to judge how they would use a tool in a particular environment (e.g., “Take the pencil to write on a sheet of paper”). Prior to this tool-use judgment task, some participants had been immobilized (right arm) for 24 hours. Results revealed that compared with controls, immobilized participants performed more poorly on the tool-use judgment task (accuracy and response time) as well as in a manual dexterity task. As our tool-use judgment task involved anticipating the expected perceptual effect of using a tool to achieve an environmental goal (e.g., writing on a sheet of paper), our data are discussed in line with theories of motor control (e.g., ideomotor theory) that emphasize the expected perceptual consequences of the action.

Introduction

Being able to anticipate tool use in the environment is a fundamental cognitive ability when it comes to efficiently regulating our daily lives (Bongers, Michaels, & Smitsman, 2004; Osiurak & Badets, 2017). For example, if we want to slice tomatoes for the next meal, we know exactly how we will use the knife to do so. However, this motor anticipation can be greatly weakened in situations such as limb injury in stroke (Lissek et al., 2009). For example, after a month-long recovery from a broken arm, a gardener may worry about being able to use the tools appropriately in all the different tasks. This type of impairment is thought to involve motor anticipation, and the aim of the present study was to assess this hypothesis through a laboratory paradigm of limb immobilization.

From a theoretical point of view, we postulated that the motor anticipation of tool use is probably based on the expected perceptual effect of a to-be-enacted action (for the theory, see Badets & Osiurak, 2015; see also Massen & Prinz, 2009). According to Badets and Osiurak (2015), a goal-based mechanism “assumes that when people have to use a tool, they first form a representation of the expected perceptual consequences of the mechanical actions (the hammer pounding the nail), which then guide the movements to be executed” (p. 352). This cognitive representation of the expected perceptual consequences of a tool’s action in the environment is reminiscent of ideomotor theory (Greenwald, 1970; Pfister, 2019). According to this theory, representing the expected perceptual (visual, auditory, tactile, or

proprioceptive; Pfister, 2019) effects in the environment allows the appropriate body movements to be selected and planned. For example, if a person wishes to put a bottle of wine on a high shelf, the manual grip will automatically be on the lower part of the bottle, reflecting the anticipation of the expected perceptual effect in the environment (i.e., bottle on high shelf). More specifically, the person will efficiently select the most comfortable end-state body posture (grip on the bottle) based on environmental (top shelf) information. This phenomenon can be seen as a feeling to avoid uncomfortable movement plus the final position toward the object, and has been described by Rosenbaum and colleagues under the term “end-state comfort” effect (Rosenbaum et al., 1990). According to Wunsch and colleagues (2013), the mechanisms underlying this effect could also come from a “posture-based planning account” (see also Rosenbaum et al., 2007). In this view, from a starting posture, several possible postures are analyzed in order to process the best one for a future and better goal posture. Then, this goal posture anticipation permits the selection of the relevant movement. Consequently, without denying the implication of the posture-based approach, we assumed that motor anticipation of tool-use is first governed by an ideomotor mechanism that anticipates the expected perceptual effects in the environment, which in turn permits to efficiently regulate the most relevant body movement (Badets & Osiurak, 2015; 2017; Janczyk, Yamaguchi, Proctor, & Pfister, 2015).

To assess whether the perceptual effect of tool-use is genuinely anticipated, Badets, Duville, and Osiurak (2020) recently applied a dual-task paradigm that required participants to retain a particular tool-use in their mind while performing an unrelated secondary task. Specifically, during this secondary task the participants were required to keep in mind that after a specific stimulus, they will have to use a tool toward the environment. The theoretical question was whether this “keeping in mind” procedure involved for participants mainly the hand movement toward the tool (i.e., body posture), or the movement of the tool toward the environment (i.e., expected perceptual effect). More specifically, participants were told they would be shown stimuli like Arabic numbers from 1 to 9 printed in different colors. As a practice trial, two numbers were displayed on a computer screen, and the task was to decide whether the numbers were printed in identical or different colors (i.e., the unrelated secondary task). Importantly, when the two numbers had the same parity (i.e., even-even or odd-odd), participants had to switch to a tool-use task (i.e., prospective task). Only 16% of the trials in the experimental session triggered this tool-use task, meaning that participants constantly had to keep the intended tool action in mind. Results revealed an interaction between number processing and the action of the tool. More specifically, initiation of the closing action of the tool was slower after the processing of large numbers, indicating that the processing of this closing and then small movement were incompatible with the processing of large numbers (for similar incompatible effect between small hand movements and large number processing, see Andres, Ostry, Nicol, & Paus, 2008; Ranzini et al., 2011). The authors concluded that in 84% of the ongoing trials, the intention to use the tool was coded in terms of the tool’s action. The perceptual effect of tool-use is therefore principally anticipated, even during an unrelated task.

All the experiments described above involved enacted body movement, and it is not yet known whether immobilization can also affect the anticipation of a body movement involving a tool in the absence of real enactment. In the domain of neuroimaging, short-term

immobilization can lead to sensorimotor perturbations. A decreased in cortical excitability has been reported in motor and/or somatosensory cortices after a brief period of upper limb immobilization ranging from 10-12 hours (Avanzino, Bassolino, Pozzo, & Bove, 2011; Huber, Ghilardi, Massimini, Ferrarelli, Riedner, Peterson, & Tononi, 2006) to 3-4 days (Facchini, Romani, Tinazzi, & Aglioti, 2002; Ngomo, Leonard, & Mercier, 2012). In the domain of motor control, the short immobilization of a limb is known to affect human behavior (for seminal studies, see Huber et al., 2006; Toussaint & Meugnot, 2013; for a peripheral musculature account, see Seki, Taniguchi, & Narusawa, 2001; and for a central nervous system account, see Kaneko, Murakami, Onari, Kurumadani, & Kawaguchi, 2003). To assess the impact of the short-term immobilization of a limb on the control of aiming movements, Scotto and colleagues (2020) immobilized the right arm of participants for a 24-hour period. Findings revealed that, compared with a control group (i.e., no immobilization procedure), aiming behavior was poorer, in terms of both acceleration and deceleration of the arm movement toward the target. These results show that both the feedforward (i.e., early impulse phase) and feedback (i.e., later online correction phase) processes of motor control were impacted by the short-term arm immobilization. Using the same immobilization procedure, Toussaint, Meugnot, and Bidet-Ildei (2021) went further, by examining the effects of hand immobilization on the covert stage of action (i.e., before the movement begins), focusing on the immobilization-induced effects on the content of the motor program used for grasping small versus large objects. They reported that the usual grip-precision effect (i.e., lower response times when grasping small vs. large objects) disappeared in the immobilized group. The authors suggested that short-term immobilization was sufficient to impair grasp representation, thereby making it harder for participants to retrieve an internal model with concrete information on the grasping movement. Other studies have focused on the covert stage of action, by examining the immobilization-induced effect on motor imagery processes using body-part mental rotation tasks (also hand/foot laterality tasks as a function of the body part involved; Meugnot, Agbangla, & Toussaint, 2016). Toussaint and Meugnot (2013) found that after 2 days of arm immobilization, participants performed a hand mental rotation task more poorly than a control group. They concluded that motor imagery strategy is impaired by a short-term immobilization procedure that reduces proprioceptive feedback processing, but other higher cognitive processes considered independent of sensorimotor information (e.g., visual imagery) are not affected.

Capitalizing on the findings described above for the motor control domain, the main goal of the two experiments described below was to assess the effect of a short-term immobilization procedure (24 hr) on cognitive motor processes not yet studied in the literature: motor planning, and more particularly the ability to anticipate tool-use. More specifically, we used an end-state comfort task (Rosenbaum et al. 1990) to test the hypothesis that an immobilization procedure can impair the ability to anticipate the expected perceptual effect of a tool on the environment.

Experiment 1

We used a pre-/posttest paradigm to best capture the effect of a 24-hr immobilization procedure on tool-use judgment (Toussaint & Meugnot, 2013). We predicted that after the

immobilization procedure, participants would perform more poorly on an anticipatory tool-use task.

In addition, we examined the link between performance on this tool-use judgment task and motor imagery ability, assessed with the Vividness of Movement Imagery Questionnaire (VMIQ; Isaac, Marks, & Russell, 1986) to measure both motor (i.e., first-person perspective) and visual (i.e., third-person perspective) imagery. Toussaint and Meugnot (2013) had previously highlighted the important role of imagery in cognitive motor processes. They reported that participants who had a lower ability to mentally simulate a movement (i.e., first-person perspective of VMIQ) were more liable to abandon the use of a motor imagery strategy to perform the hand laterality task when their sensorimotor system was affected by a short period of immobilization.

Method

Participants

We conducted an a priori analysis (F tests) using GPower 3.1 (Faul et al., 2007) to test the differences between two groups (normal and immobilized) and two sessions (pretest and posttest), with a medium effect size ($f=0.25$), an alpha of .05 and a repeated measure correlation of .50. The results indicated that we needed to include at least 46 participants to achieve a power of 0.90. A total of 50 university students (age range: 18-23 years) voluntarily participated in this experiment in exchange for a course credit or a payment of €20. All participants provided their written informed consent before the experiment began. The study complied with the Declaration of Helsinki and was approved by the local ethics committee (n° 202054). Participants were naive to the aims of the experiment. They were self-declared right-handed, had normal or corrected-to-normal vision, and had no past or present nervous or muscular disorders.

Participants were randomly assigned to either a control group ($n = 25$; mean age = 19.4 years, $SD = 1.0$ years; 13 females) or an immobilized group ($n = 25$; mean age = 19.2 years, $SD = 1.3$ years; 12 females). The data of one participant in the immobilized group were subsequently excluded from the analyses because his reaction times differed by more than 2.5 standard deviations from his group mean. All participants completed the VMIQ (Isaac et al., 1986) prior to the experiment, to control for differences in motor imagery ability. The VMIQ consists of 24 items measuring the vividness of movement imagery from either an external (i.e., movement simulated from a third-person perspective) or internal (i.e., movement simulated from a first-person perspective) perspective. Each item is rated on a 5-point Likert-type scale ranging from 1 (*Perfectly clear and as vivid as normal vision*) to 5 (*No image at all*). Therefore, for each imagery perspective, scores can range from 24 to 120. Independent sample t-test were performed to compare the VMIQ scores between groups for each perspective. Participants' scores (Table 1) indicated good imagery ability, with no significant differences between groups.













Table 1. Mean (Standard Deviation) VMIQ scores for internal and external perspectives for both control and immobilized groups.

| | Control group | Immobilized group | |
|----------------------|---------------|-------------------|---------------------------|
| Internal perspective | 39 (13) | 42 (14) | $t(47) = -0.78, p = 0.44$ |
| External perspective | 43 (11) | 43 (13) | $t(47) = -0.01, p = 0.99$ |

Material, task and experimental procedure

Participants performed a tool-use judgment task. Six different tools (i.e., pencil, flower, ice pick, mallet, bottle, and paint roller) were displayed on a computer screen placed 50 cm in front of them. The tools were shown in two different orientations, with their functional part being either on the left or on the right (Table 2). To prevent participants from adopting a strategy whereby the left/right location of the functional part dictated whether the tool had to be grasped from above/below, the functional part of the tools oriented to require an overhand grip was on the right for half of them (i.e., pencil, flower, ice pick), and on the left for the other half (i.e., mallet, bottle, paint roller). The expected grasp according to the orientation of the tool had previously been tested on 64 participants (not included in the present experiment) in a pilot study featuring a larger number of tools. For the present study, we selected the six tools that were grasped in the same way more than 80% of the time (Table 2).

Table 2. Illustration of stimuli with expected grasp according to tool orientation.

| Associated action | Expected grasp “from above” | Expected grasp “from below” |
|--|---|---|
| Take the pencil to write on a sheet |  |  |
| Take the flower to put it in a vase |  |  |
| Take the ice pick to plant it on the table |  |  |
| Take the mallet to drive in a dowel |  |  |
| Take the bottle to fill a glass |  |  |
| Take the paint roller to paint a wall |  |  |

Before a tool appeared on the computer screen, a sentence describing its associated action was displayed for 3.5 s (Table 2). First, participants were asked to read aloud the sentence, so that the experimenter could ensure that they had read the instructions for the action associated with a specific object. They then were asked to judge, as fast and accurately as possible, whether the tool should be grasped from above or below, depending on the described action. They had to press the “q” (top) or “s” (bottom) key on a qwerty keyboard with the middle or index finger of their left hand to give a “from above” or “from below” response (Figure 1). A white screen (500 ms) separated successive trials. A white screen (500 ms) separated successive trials.

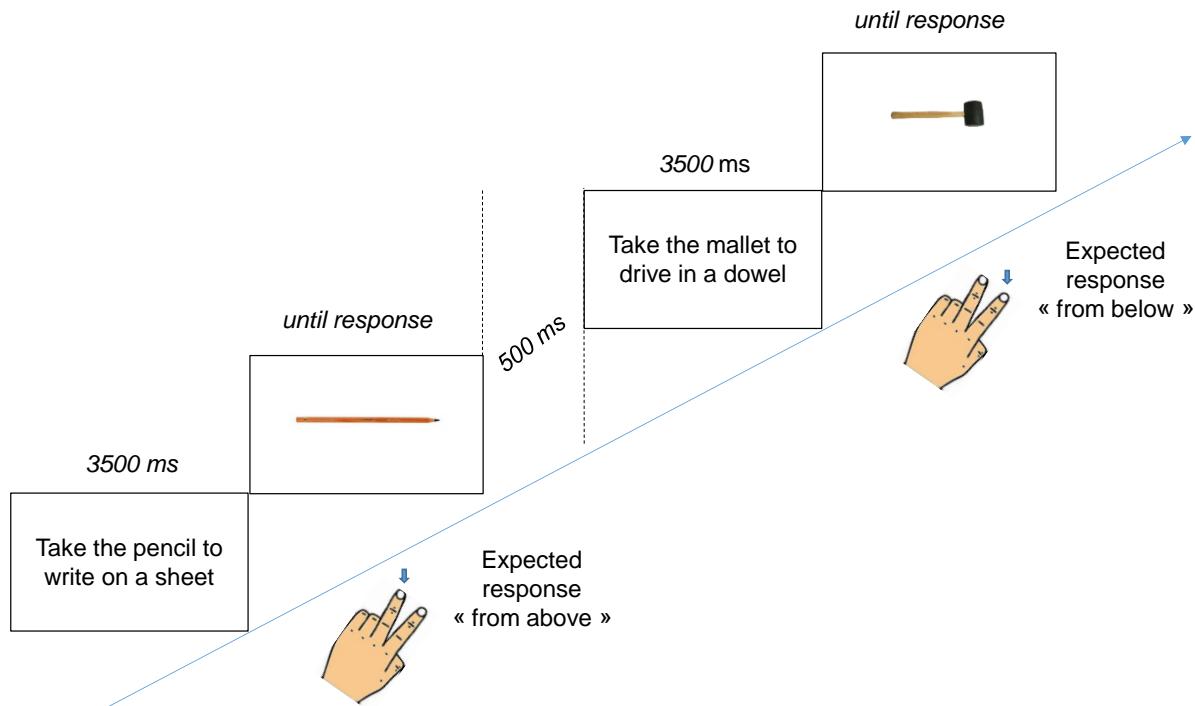


Figure 1. Procedure of the tool-use judgment task.

We used the E-Prime 2.0 software package (Psychology Software Tools Inc., Pittsburgh, PA, USA) to display the sentences and tools, as well as to record participants' response times and answers. Response time corresponded to the time between the appearance of a tool and the participant's response. A response was considered correct if it matched the expected response (as illustrated in Table 2).

Participants performed the tool-use judgment task in two experimental sessions (pretest and posttest) 24 hours apart. In the case of the immobilized group, the pretest was performed before the immobilization, and the posttest immediately afterwards. Participants were instructed to put their right hand at rest on their legs and to inhibit any hand and finger movements to avoid sensorimotor awakening. Participants in the control group took the same position. To ensure that participants in the immobilized group kept their right upper limb at rest during the immobilization period, we attached a rigid splint (DonJoy Comfort Digit; DJO, Surrey, United Kingdom) on their right hand, and an immobilization vest restrained their right shoulder, arm and forearm (DonJoy Immo Axmed). We monitored the movements of both

hands using actimeters that quantified limb accelerations in three axes, converted into counts/min. During the 24-hour period, an average of 2828 counts/min (SD = 897) were recorded for participants' left hand and 687 counts/min (SD = 416) for their immobilized right hand (for a similar procedure, see Toussaint & Meugnot, 2013). An ANOVA on actimeter values confirmed that there were significantly fewer limb movements for the immobilized right hand than for the left hand, $F(1,23) = 176.03$, $p < .001$, $\eta^2_p = 0.88$.

For each participant in each group (i.e., control and immobilized), we recorded a total of 60 responses for the tool-use judgment task (i.e., 5 blocks of 6 tools each with 2 expected grasps) in each session (i.e., pretest and posttest). The tools were presented randomly in each block. Each session lasted approximately 10 minutes.

Data analysis

Response accuracy (i.e., percentage of correct responses) and response times were recorded for each trial. Only response times for correct responses were analyzed. We checked whether all variables were normally distributed using the Shapiro-Wilk test before performing ANOVAs. Only accuracy did not show a normal distribution. For this variable, we calculated the difference between the posttest and the pretest for each participant in each group. A positive value indicates an improvement in performance, while a negative value indicates a deterioration in performance. The difference between the control and the immobilized groups was assessed by a non-parametric Mann-Whitney test. For response times, an ANOVA was performed with group (i.e., control vs. immobilized) as the between-participants factor and session (i.e., pretest vs. posttest) as the within-participants factor. Significant interactions were investigated further with Tukey multiple comparison post hoc tests. Alpha was set at .05 for all analyses.

Results

Tool-use judgment task

The accuracy was 82% (SD = 12%) and 83% (SD = 11%) in pretest, and 93% (SD = 7%) and 89% (SD = 12%) in posttest, in the control and immobilized groups respectively (see Figure 2). Mann-Whitney test showed that the difference between pretest and posttest significantly differed between groups ($U = 415$, $p = .02$), with a higher increase in accuracy in the control group (mean = 11%, SD = 8%) than in the immobilized group (mean = 5%, SD = 7%). Wilcoxon signed-rank tests were then used to examine whether the difference in pretest and posttest significantly differed from zero for each group. Significant results were shown for both the control, $V(24) = 253$, $p < .001$, and immobilized, $V(23) = 239$, $p < .002$, groups.

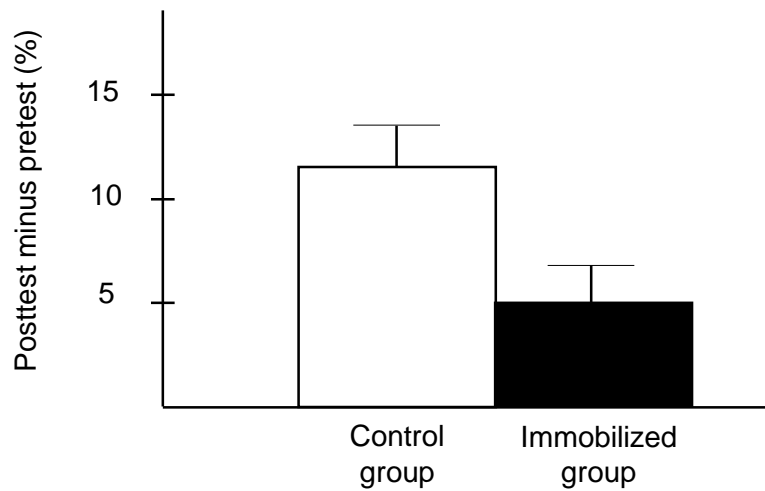


Figure 2. Difference between pretest and posttest (%) for the control and immobilized groups in the tool-use judgment task. Error bars indicate the standard error of the mean.

The ANOVA performed on *response times* revealed only a main effect of Session, $F(1,47) = 66.92$, $p < .001$, $\eta^2 p = 0.59$, with longer response times at pretest (mean = 2072; SD = 671 ms) than at posttest (mean = 1489; SD = 580 ms). There was no effect of Group, $F(1,47) = 0.94$, $p = .34$, and no Group x Session interaction, $F(1,47) = 0.24$, $p = .63$.

Correlations between performance on tool-use judgment task and imagery ability.

Since the accuracy data were not normally distributed, we used Spearman's rank correlation to examine the relationship between action planning and imagery ability. We therefore calculated correlation between performance on the tool-use judgment task (i.e., accuracy vs. response times) and VMIQ scores (i.e., internal vs. external perspectives) for the control and immobilized groups at pretest and posttest. As illustrated in Table 3, significant correlations were found for both groups, but only between response times and internal and external VMIQ scores at pretest. Note however that the differences between correlation coefficients in pretest and in posttest, computed using Z-test (Meng et al., 1992), were not significant (control: $p_s > .10$; immobilized: $p_s > .22$).

Table 3. Spearman correlation coefficients between performance on the tool-use judgment task (accuracy and response times) at Pretest and Posttest and VMIQ scores (internal and external perspectives).

| Tool-use judgment task | | VMIQ Scores | |
|----------------------------|----------|----------------------|----------------------|
| | | Internal perspective | External perspective |
| Accuracy (%) | | | |
| Control group (N=25) | Pretest | 0.26 <i>ns</i> | 0.17 <i>ns</i> |
| | Posttest | 0.18 <i>ns</i> | 0.08 <i>ns</i> |
| Immobilized group (N=24) | Pretest | 0.06 <i>ns</i> | 0.16 <i>ns</i> |
| | Posttest | -0.07 <i>ns</i> | -0.06 <i>ns</i> |
| Response times (ms) | | | |
| Control group (N=25) | Pretest | 0.45 * | 0.45 * |
| | Posttest | 0.23 <i>ns</i> | 0.20 <i>ns</i> |
| Immobilized group (N=24) | Pretest | 0.45 * | 0.40 * |
| | Posttest | 0.25 <i>ns</i> | 0.26 <i>ns</i> |

Note, *ns*: no significant correlation. * $p < .05$.

These significant positive correlations revealed that participants who performed the tool-use judgment task faster (i.e., shorter response times) had greater imagery ability (i.e., lower imagery scores), but only in the first session (i.e., pretest; Figure 3).

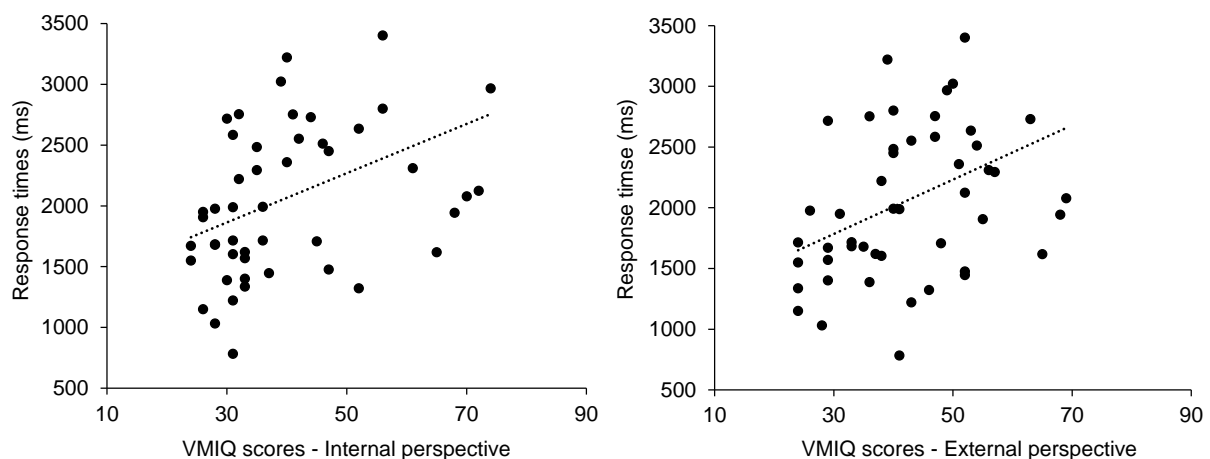


Figure 3. Correlations between response times (ms) in the tool-use judgment task at pretest and VMIQ scores for both internal and external perspectives for all participants.

Discussion

Accuracy results indicated that the tool-use judgments of participants who underwent the immobilization procedure improved less than those of controls. In line with the practice effect, whereby performance improves with practice (Heathcote, Brown, & Mewhort, 2020),

both groups' performances on the tool-use judgment task improved across the two sessions. However, the control group achieved better scores. Consequently, in the tool-use domain, performance on a task requiring participants to anticipate an expected perceptual effect on the environment with no associated overt action is impaired by immobilization. This finding reinforces the literature on the immobilization-induced effect on motor control in humans (Scotto et al. 2020; Toussaint & Meugnot, 2013; Toussaint, Meugnot, & Bidet-Ildet, 2021). These authors observed an effect on response programming (corresponding to response times), but not on response selection (corresponding to response accuracy).

We did not find a relationship between posttest response times on the tool-use judgment task and imagery ability. This relationship was only observed for the pretest, across both groups. Response times were longer at pretest than at posttest. We can therefore speculate that a correlation only appeared when response times were long enough not to diminish cognitive performances. More specifically, participants benefited cognitively from longer response times, as it took time to process the relevant information (Badets et al., 2013). Thus, it could be hypothesized that longer response times permitted the strengthening of a more robust cognitive representation of the expected movement during the tool-use judgement task that in turn can more toughly correlate with the imagery representation capacity. Testing this point could be a good perspective for future studies.

The goal of the second experiment was to further assess the effect of immobilization on response selection without the potential *ceiling effect* induced by shorter response times at posttest in Experiment 1.

Experiment 2

In this second experiment, we only used a delayed test (i.e., posttest in a single experimental session), so that reaction times would be long enough not to impair cognitive performances on the tool-use judgment task. In addition, we used a manual dexterity task as a control condition, expecting to observe similar motor performances for the non immobilized left hand in both groups. The left hand was not immobilized, so if participants in the two groups were equal in terms of basic motor control, we would not observe any effect of the immobilization procedure for this limb. The manual dexterity task also served to examine whether performance on the tool-use judgment task was linked to motor performance.

Method

Participants

Fifty-two university students aged 18-23 years took part in the experiment on a voluntary basis. They were self-declared right-handed, had normal or corrected-to-normal vision, and had no past or present nervous or muscular disorders. Participants took part in exchange for a course credit or a payment of €20. They provided their written informed consent before the experiment began. The study complied with the Declaration of Helsinki and was approved by the local ethics committee (n° 202054). Participants were naive to the aims of the experiment. They were randomly assigned to either the control group ($n = 27$; mean age = 21.3 years, $SD = 2.3$ years; 13 females) or the immobilized group ($n = 25$; mean

age = 21.5 years, $SD = 2.4$ years; 16 females). The data of two participants in the control group were subsequently excluded from the analyses because their reaction times differed by more than 2.5 standard deviations from their group mean.

Prior to the experiment, participants completed the VMIQ (Isaac et al., 1986) to control for differences in motor imagery ability. Participants' scores (Table 4) indicated good imagery ability, with no significant differences between the groups (independent sample t-test).

Table 4. Mean (Standard Deviation) VMIQ scores for internal and external perspectives for control and immobilized groups.

| | Control group | Immobilized group | |
|----------------------|---------------|-------------------|---------------------------|
| Internal perspective | 41 (12) | 43 (10) | $t(48) = -0.79, p = 0.43$ |
| External perspective | 47 (15) | 48 (12) | $t(48) = -0.05, p = 0.96$ |

Material, task and experimental procedure.

Participants first performed the same tool-use judgment task as in Experiment 1. For each participant in each group (i.e., control and immobilized), we recorded 60 responses (i.e., 5 blocks of 6 objects each with 2 possible orientations/grasp) in a single experimental session. Participants then performed a manual dexterity task, first with their left hand, then with their right hand. A rectangular board with 12 horizontal rows of four holes and a cup at the top was placed on the table in front of participants. The cup contained small plastic pegs (mushroom-shaped; straight section: 10 mm high, 4 mm in diameter; Round top: 5 mm high, 9.5 mm in diameter). Participants had to remove the pegs one by one and place them in the holes as quickly as possible. They filled the rows from the top, from left to right with their right hand, and from right to left with their left hand. We recorded the number of pegs placed in holes within 30 s for each hand.

For participants in the immobilized group, we fixed a rigid splint (DonJoy Comfort Digit; DJO, Surrey, United Kingdom) to their right hand and an immobilization vest restraining their right shoulder, arm and forearm (DonJoy Immo Axmed) 24 hours before they performed the experimental tasks described above. The tool-use judgment task and the manual dexterity task were performed immediately after removal of the splint and vest. As in Experiment 1, we monitored the hand movements of both hands using actimeters that quantified limb accelerations in three axes, converted into counts/min. During the 24-hour immobilization period, an average of 2641 counts/min ($SD = 809$) were recorded for participants' left hand, and 566 counts/min ($SD = 214$) for their immobilized right hand. An ANOVA on actimeter values confirmed that there were significantly fewer limb movements for the immobilized right hand than for the left hand, $F(1,24) = 232.29, p < .001, \eta^2 p = 0.91$.

Data analysis

Response accuracy (i.e., percentage of correct responses) and response times were recorded for each trial. Only response times for correct responses were analyzed. We checked whether all variables were normally distributed using the Shapiro-Wilk test. Only accuracy did not show a normal distribution. For this variable, we therefore assessed the difference between the groups using a non-parametric Mann-Whitney test. For response times, an ANOVA was performed with group (control vs. immobilized) as a between-participants factor.

Scores on the manual dexterity task (i.e., number of pegs placed within 30 s) were analyzed with an ANOVA, with group (i.e., control vs. immobilized) as a between-participants factor and hand (i.e., left vs. right) as a within-participants factor. Significant interactions were investigated further with Tukey multiple comparison post hoc tests. Alpha was set at .05 for all analyses.

Results

Tool-use judgment task

The non-parametric Mann-Whitney test performed on *accuracy* revealed a significant difference between both groups ($U = 421$, $p = .03$), with less accuracy in the immobilized group (mean = 73%, SD = 15%) than in the control group (mean = 83%, SD = 12%). The ANOVA performed on *response times* also yielded a significant effect of Group, $F(1,48) = 5.77$, $p < .025$, $\eta^2 p = 0.11$, with longer response times in the immobilized group (mean = 1885 ms; SD = 756 ms) than in the control group (mean = 1479, SD = 339 ms).

Manual dexterity task

The ANOVA performed on *manual dexterity scores* revealed a main effect of Group, $F(1,48) = 11.07$, $p < .005$, $\eta^2 p = 0.19$, a trend toward significance for the main effect of Hand, $F(1,48) = 3.52$, $p = .067$, $\eta^2 p = 0.7$, and a significant Group x Hand interaction, $F(1,48) = 18.70$, $p < .001$, $\eta^2 p = 0.28$. As seen in Figure 4, fewer pegs were placed in holes within 30 seconds by the right hand in the immobilized group than in the control group ($p < .001$), whereas there was no difference between groups for the left hand ($p = .36$). In the immobilized group, scores were lower for the immobilized right hand than for the left hand ($p < .001$).

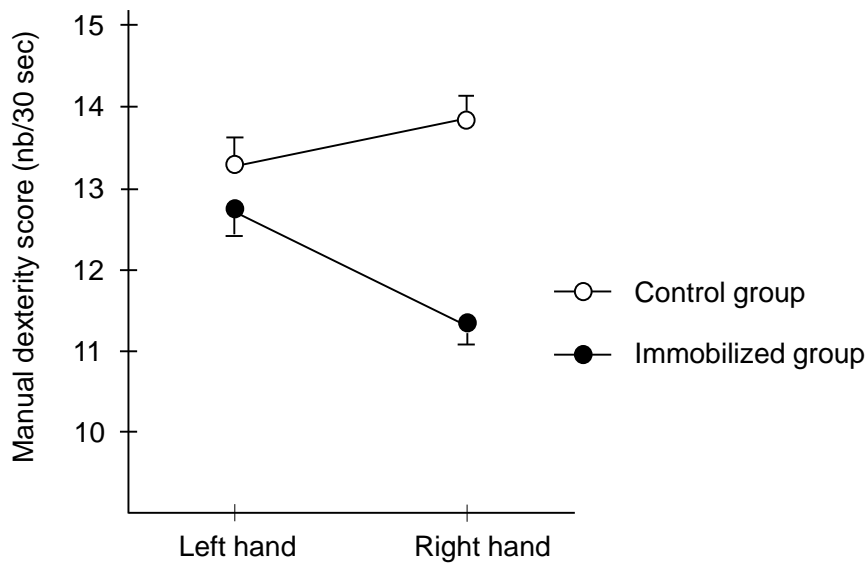


Figure 4. Scores (number of pegs placed within 30 s) on the manual dexterity task as a function of group and hand. The right hand had previously been immobilized for 24 hours in the immobilized group. Error bars indicate the standard error of the mean.

Correlations between performance on tool-use judgment task and scores on manual dexterity task

Since the accuracy data were not normally distributed, we used Spearman's rank correlation to examine the relationship between action planning and manual dexterity. We therefore calculated correlation between performance on the tool-use judgment task (i.e., accuracy and response times) and manual dexterity (left and right hands) scores for the control and immobilized groups. As illustrated in Table 5, significant correlations only emerged in the immobilized group, between accuracy on the tool-use judgment task and dexterity of the immobilized right hand. No significant difference appeared between correlation coefficients for left and right and in the immobilized group (Z-test; $p = .42$).

Table 5. Pearson correlation coefficients between performance on tool-use judgment task (i.e., accuracy and response times) and scores on manual dexterity task for left and right hands.

| Object-grasping judgement | Manual dexterity scores | |
|----------------------------|-------------------------|-----------------|
| | Left hand | Right hand |
| Accuracy (%) | | |
| Control group (N=25) | 0.12 <i>ns</i> | 0.15 <i>ns</i> |
| Immobilized group (N=25) | 0.36 <i>ns</i> | 0.53 ** |
| Response times (ms) | | |
| Control group (N=25) | -0.33 <i>ns</i> | -0.18 <i>ns</i> |
| Immobilized group (N=25) | -0.21 <i>ns</i> | 0.30 <i>ns</i> |

Note, *ns*: no significant correlation. ** $p < .01$.

The significant positive correlation between accuracy on the tool-use judgment task and the manual dexterity score revealed that participants who had poorer planning ability (i.e., less accurate tool-use judgment) performed the manual dexterity task more slowly (i.e., fewer pegs within 30 s) after 24 hours of right-hand immobilization (Figure 5).

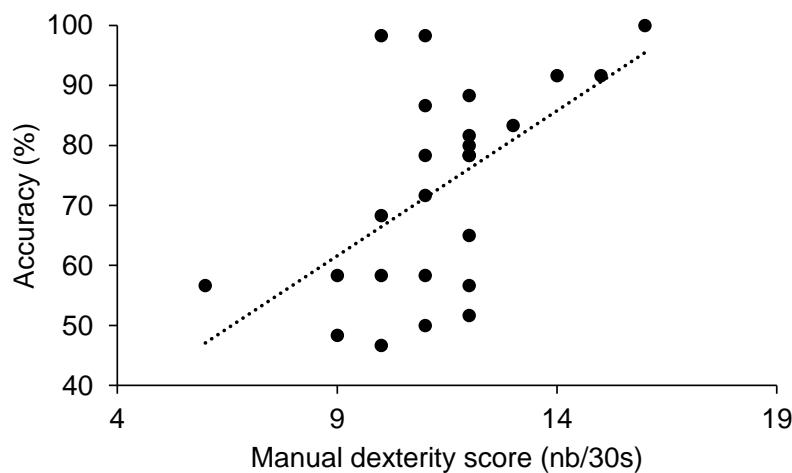


Figure 5. Correlation between tool-use judgment accuracy (%) and manual dexterity score (immobilized right hand) for the immobilized group.

Correlations between performance on the tool-use judgment task and imagery ability.

As in Experiment 1, we examined Spearman's rank correlation between performance on the tool-use judgment task (i.e., accuracy and response times) and VMIQ scores (i.e., internal and external perspectives) for the control and immobilized groups. As illustrated in

Table 6, significant correlations only emerged for response times in the control group (with no significant differences between both perspectives; Z-test, $p = .73$). As in Experiment 1, no significant correlation was found after 24 hours of immobilization.

Table 6. Pearson correlation coefficients between performance on tool-use judgment task (accuracy and response times) and VMIQ scores (internal and external perspectives).

| Object-grasping judgement | VMIQ Scores | |
|----------------------------|----------------------|----------------------|
| | Internal perspective | External perspective |
| Accuracy (%) | | |
| Control group (N=25) | 0.17 <i>ns</i> | 0.23 <i>ns</i> |
| Immobilized group (N=25) | 0.25 <i>ns</i> | 0.27 <i>ns</i> |
| Response times (ms) | | |
| Control group (N=25) | 0.51 ** | 0.47 * |
| Immobilized group (N=25) | 0.28 <i>ns</i> | 0.27 <i>ns</i> |

These significant positive correlations indicated that participants who performed the tool-use judgment task faster (i.e., shorter response times) had higher imagery ability (i.e., lower imagery scores; Figure 6).

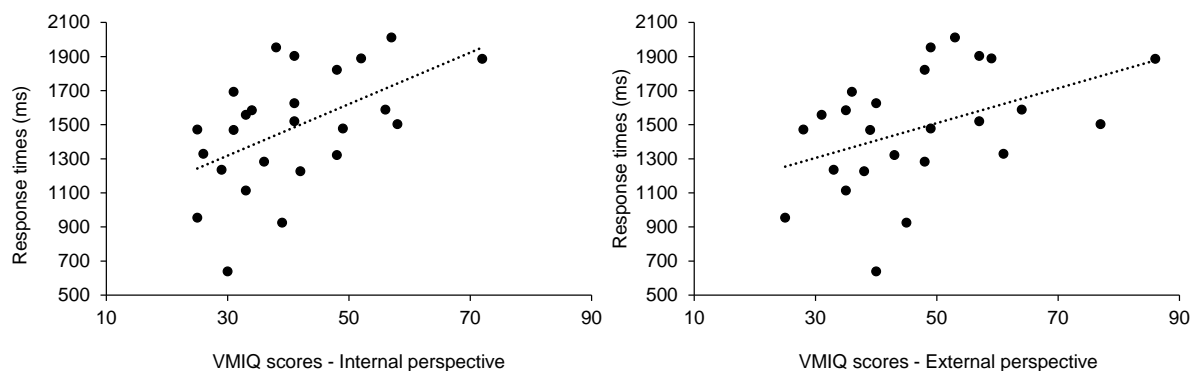


Figure 6. Correlations between response times (ms) in tool-use judgment task and VMIQ scores for both internal and external perspectives for the control group.

Discussion

Response selection results, as assessed by the accuracy of responses in the tool-use judgment task, revealed the same finding as in Experiment 1. Participants who underwent the immobilization procedure were less accurate than controls. Moreover, results on response times revealed the same finding as in previous studies (Scotto et al. 2020; Toussaint &

Meugnot, 2013; Toussaint, Meugnot, & Bidet-Ildei, 2021), with poorer performance after immobilization. For the control group, the positive correlation between response times and imagery ability, as assessed by the VMIQ, indicates that imagery needed time, and protected the anticipatory mechanism in the tool-use judgment task. In line with this view, no correlation was found for the immobilized group, and we can speculate that immobilization impaired participants' imagery ability, which, in turn, had a negative impact on performance on the tool-use judgment task. Results of the manual dexterity task showed that both groups were equal in terms of performance for the left hand, indicating similar levels for a basic motor control task across the two groups. However, immobilization reduced performance, indicating a general effect of this restriction procedure. Immobilization can impair performance on a tool-use judgment task, but also on an unrelated motor task such as manual dexterity.

General discussion

The main goal of the present study was to assess whether an immobilization procedure can weaken the ability to anticipate the expected perceptual effect of a tool on an environment. To this end, we administered an end-state comfort task (Rosenbaum et al., 1990) that is known to elicit anticipatory mechanisms (Osiurak & Badets, 2017). More specifically, participants were required to judge whether a tool should be grasped from below or above, depending on the end-state posture. Results of the first experiment revealed that the immobilization procedure impaired the selection of the response (i.e., accuracy). This result was replicated in Experiment 2, which also testified to the adverse effect of immobilization on the response anticipation of tool use (i.e., response times). As suggested by Badets and Osiurak (2015), before acting on a tool, people activate a cognitive representation of the expected perceptual effect of the tool on the environment (Greenwald, 1970; Pfister, 2019). During the task, the physical problems afforded by the environment force the activation of such representation, measurable by an end-state comfort posture (Osiurak & Badets, 2017). This ideomotor mechanism was specifically impacted by the immobilization procedure used in the present study. The ideomotor theoretical account is discussed below.

Both experiments revealed a correlation between imagery ability, as assessed by the VMIQ, and response times for the tool-use judgment task. In the first experiment, this effect was observed for both the immobilization and control groups at pretest, so prior to the experimental manipulation. In the second experiment, it was observed at the delayed test, but only for the control group (i.e., no immobilization procedure). Consequently, it could be argued that this correlation requires an intact programming mechanism for the judgment task that is not impaired by immobilization. This finding echoes Brass, Bekkering, and Prinz (2001), who suggested that from an ideomotor perspective, when an action is relatively complex, it requires more time-consuming processing to reach the adequate threshold for efficient action programming. Here, data showed that either time (longer response times at pretest than at posttest in Experiment 1), or an intact programming mechanism (control group at delayed test in Experiment 2) was needed for there to be a correlation with another cognitive task (e.g., VMIQ).

It is important to emphasize that in the present study, we used a priming context taken from an action-effect sentence reading task (Bidet-Ildei et al., 2017). These authors found that reading sentences such as “The neighbor is running in the garden” improved the detection of biological movement (e.g., real-world running action). This priming effect was consistent with the embodied cognition account, suggesting that language and abstract thought arise from sensorimotor experience (Barsalou, 1999). In the present study, our sentences mainly involved the expected final goal of the action (e.g., “Take the flower to put it in a vase”). Here, “put it in a vase” probably encouraged participants to engage in the cognitive simulation of this expected perceptual effect (i.e., “in a vase”), which in turn primed the response selection during the tool-use judgment task. This kind of cognitive activity involves simulating a situated, real-world environment, as suggested by Wilson (2002). For this author, “situated cognition involves interaction with the things that the cognitive activity is about” (p. 626). Our tool-use anticipation task was clearly a good candidate for the *things* (expected perceptual effect; e.g., “in a vase”) concerned by the *cognitive activity* (selection of appropriate action; i.e., grasping the tool from above or below) (see Table 2). The end-state body posture paradigm (Rosenbaum et al., 1990) used in the present study represents an ideal condition for considering situated cognition.

When it comes to the *specific* nature of the expected perceptual effect, this theoretical account seems less convincing, given that the unrelated dexterity manual task in Experiment 2 was also impacted by the immobilization procedure. This kind of manual task, and the associated sensorimotor mechanisms assessed during motor execution, is less about perceived effects than about individuals’ ability to use their fingers and hand to perform the task (Opie, Evans, Ridding, & Semmler, 2016). Nevertheless, Scotto and colleagues (2020) confirmed experimentally that short-term immobilization can impair sensorimotor expectation during a comparable continuous task, and also impairs its executive control throughout sensory feedback processing. Moreover, our second experiment revealed a strong correlation between the manual dexterity task and the accuracy score of the tool-use judgment task. As we believe that the judgment task relied primarily on an ideomotor mechanism, we suggest that a perceptual mechanism was also impacted during the dexterity task. However, the present paradigm used in the present study cannot firmly disentangle the different conclusions from the expected perceptual effect of the movement or the anticipation of the posture-based planification account suggested by Rosenbaum and colleagues (2007; see also Wunsch and colleagues, 2013). In this perspective, the movement of the dexterity manual task, and the movement of the planned posture of the judgement task interacted, and more studies are needed in order to decisively confirm the main involvement of the expected perceptual mechanism.

Taken together, our results indicate that immobilization influences all cognitive and motor mechanisms behind motor control in humans. Kunde, Koch, and Hoffmann (2004) have already suggested that the ideomotor mechanism exerts its influence not only during the early process of response production (i.e., response selection), but also during response execution. Nevertheless, immobilization is acknowledged to mainly impact the processing of proprioceptive feedback (Toussaint & Meugnot, 2013), which is rarely encompassed in ideomotor theories (Badets & Osiurak, 2015; Hommel et al. 2001). We therefore have

reservations about a proprioceptive account of the effect of immobilization on the ideomotor mechanism.

Despite the fact that ideomotor theories and empirical findings have mainly capitalized on distal effects such as vision and audition, which are environment-based effects (Elsner & Hommel, 2001; Kunde, 2001; for a review, see Shin, Proctor, & Capaldi, 2010), Pfister (2019) recently suggested that a body-based effect such as proprioceptive feedback could be enough for efficient action control. For example, Pfister and colleagues (2014) found that when a key-press action triggered a spatial-incompatible body-based sensory consequence such as vibrotactile information, subsequent responses were significantly delayed. Accordingly, body-based effect may represent an anticipated perceptual representation for the ideomotor mechanism. As suggested by Scotto and colleagues (2020; see also Moisello et al. 2008; Toussaint & Meugnot, 2013), because the immobilization technique is known to reduce the processing of proprioceptive signals, we can hypothesize that, conjointly with vision, body-related information about the end-posture accounted for the weakness of the immobilized group during the tool-use judgment task in the present study. More specifically, during an end-state comfort task such as putting a bottle of wine on a high shelf (Rosenbaum et al. 1990), the individual may select the most comfortable end-state body posture (i.e., grasp on the bottle) according to the expected final environment information (shelf), associated with the final proprioceptive information. Note that this interpretation is not incompatible with the postures-based approach suggested by Rosenbaum and colleagues (2007; Wunsch et al. 2013). Thus, from a starting proprioceptive-posture, several possible proprioceptive-postures are processed in order to select the best one for a future end-state position. More empirical data with the immobilized procedure are obviously required to test this visual-proprioceptive relationship during an end-state comfort task.

To conclude, we demonstrated in two experiments the negative effect of a prior immobilization procedure on performance on a tool-use judgment task. This end-state comfort task involved the cognitive anticipation of a final hand posture. This anticipation relied on the task's expected environmental constraints. Our results provide the first evidence of the effect of immobilization on this anticipatory mechanism. In terms of tool use in the real world, this means that workers should be careful about which tools to use after a lengthy recovery from a broken arm. From a theoretical point of view, more empirical investigations are needed to relate this with ideomotor theory, and to elucidate the role played by proprioceptive and/or visual information.

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Compliance with Ethical Standards

All aspects of this study were performed in accordance with the ethical standards set out in the 1964 Declaration of Helsinki and its later amendments. The study was conducted in accordance with national standards and guidelines for the protection of human participants and was approved by the local ethics committee (Internal review code 202054). All participants gave their informed consent prior to their inclusion in the study and received either course credits or €20 for their participation. All authors declare that they have no conflict of interest.

Conflict of interest

The authors declare that they have no conflict of interest.

Competing interest

The authors declare that they have no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data are available at https://osf.io/zrjy7/?view_only=9de0416d93f84cd28a081c038ed72704

Authors contribution

The authors declare that they have made substantial contributions to the conception of the present study. They contributed to the acquisition, analyses and interpretation of data. They drafted and revised the work critically and approved the later version of the manuscript.

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