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Motor imagery of tool use: relationship to actual use and adherence to Fitts' law across tasks

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Abstract

A Fitts' task was used to investigate how tools are incorporated into the internal representations that underlie pointing movements, and whether such knowledge can be generalized across tasks. We measured the speed-accuracy trade-offs that occurred as target width was varied for both real and imagined movements. The dynamics of the pointing tool used in the task were manipulated—regular pen, top-heavy tool, and bottom-heavy tool—to test the fidelity of internal representations of movements involving the use of novel tools. To test if such representations can be generalized, the orientation of the pointing task was also manipulated (horizontal vs. vertical). In all conditions, both real and imagined performances conformed to the speed-accuracy relationship described by Fitts' law. We found significant differences in imagined MTs for the two weighted tools compared to the regular pen, but not between the weighted tools. By contrast, real movement durations differed between all tools. These results indicate that even relatively brief experience using novel tools is sufficient to influence the internal representation of the dynamics of the tool-limb system. However, in the absence of feedback, these representations do not make explicit differences in performances resulting from the unique dynamics of these weighted tools.

Keywords

Tool use; Imagery; Visually guided movement; Sensorimotor control; Fitts' law; Motor learning

Introduction

In a series of three now classic experiments, Fitts (1954) demonstrated a lawful relationship between movement time and task difficulty that is known as Fitts' law and has become one of the most ubiquitous principles of human movement [for a review, see Plamondon and Alimi (1997)]. The law states that movement time is determined by the width of the targets and the amplitude of the movement required to move between them:

$$\mathrm{MT}=a+b(\mathrm{ID}) \quad (1)$$

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where MT equals the movement time; "*a*" and "*b*" are empirical constants; and ID is the index of difficulty, which is characterized by:

$$\text{ID}=\log(2A/W) \tag{2}$$

The ID, which reflects both the amplitude of movements (A) measured as the distance between the targets, and the width of the targets (W), captures task difficulty.

In one of these original experiments, Fitts' had participants make reciprocal aiming movements using pens of two different weights and observed a similar speed-accuracy trade-off for the lighter versus heavier weight pens. Although this aspect of the work has received little attention in comparison to other manipulations, it provides evidence of how motor performance can be affected by a manipulation of the dynamics of a tool; a point to which we will soon return.

In an effort to test the hypothesis that mental rehearsal of movements involves internal simulations that obey physical constraints, researchers have more recently asked whether Fitts' law accurately characterizes performances in an adaptation of Fitts' reciprocal aiming task in which participants must imagine making repeated pointing movements with a pen to a target that varies in width and/or distance (Sirigu et al. 1995, 1996; Cerritelli et al. 2000; Wilson et al. 2001; Choudhury et al. 2007). For healthy adults, the mental simulation times are indeed similarly affected by manipulations of task difficulty and appear to obey Fitts' law. This is interpreted as evidence for common internal representations underlying both actual and imagined movements.

Much like Fitts' pens, many of our daily activities involve using tools that alter the properties of the effector system (e.g., limb) that we are striving to control. The extent to which tools' mechanical and dynamical properties are incorporated into the internal motor representations remains uncertain. As mentioned earlier, Fitts' showed how the speed of motor performance was affected by adding weight to the pen. Several other studies have examined how adding weight affects imagined versus actual movements, but across studies the results have been inconclusive. Gentili et al. (2004) and Papaxanthis et al. (2002) found that added weight had a similar effect on both imagined and actual movements, while Cerritelli et al. (2000), Decety et al. (1989) and Wilson et al. (2001) found that adding weight differentially impacted imagined and actual movements. Slifkin (2008) attributes differences in these findings to the amount of weight added with respect to the participant's lifting capacity. However, another difference not mentioned is that the latter three studies used a Fitts' task and found an effect, whereas the former two studies did not vary target width or amplitude and did not find an effect of added weight on pointing movements. This suggests that differences between execution and imagery may only emerge when the precision requirements of the task are manipulated. Here, we used a Fitts' task in which precision was systematically varied, and rather than simply adding weight, we chose to manipulate tool dynamics to examine how movement representations are affected by the properties of novel tools.

To our knowledge, the question of whether manipulation of the dynamics of tools has a similar influence on mental simulation and actual MTs has received little attention. It is an important question because an affirmative answer would suggest that our internal representations capture the effects of tools' unique dynamics on motor control. This idea has received some support from two papers on grip selection suggesting that experience with a tool results in modifications of internal movement representations to accommodate the influences of the tool's unique physical properties on upper limb movements. After training to grasp objects with a novel mechanical tool, participants demonstrated a preference for grips that reflected both the tool's mechanical and dynamical properties, even when making decisions in the absence of overt movements (Jacobs et al. 2010; Martin et al. 2011). We should be able to exploit the power of Fitts' law (Fitts 1954) to evaluate whether the same speed-accuracy rules that guide actual tool use also constrain imagined tool use by looking at real and imagined MTs as a function of ID.

To determine how movement representations are affected by the properties of individual tools, we designed two novel tools that differed in their dynamical properties: a bottom-heavy pen (pendulum) and a top-heavy pen (inverted pendulum). Target width (precision) was manipulated, and Fitts' law (Fitts 1954) was used to quantify the performance for imagined pointing movements versus actual movements. If actual and imagined tool use conforms to Fitts' law, performance times should increase linearly with increases in ID. We also looked at the temporal correspondence between execution and imagery across tool types. The correlation characterizes the veridicality of imagery with respect to execution. If imagined movements are constrained by the same laws as real movements, then these correlations should be high, even when novel tools are used.

Additionally, we examined how these representations are impacted by the order of tool use. Are separate internal models used to represent movements with each individual tool, or does the evidence support updating of a single, more general model? To examine this, we manipulated tool order between four groups. Fitts (1954) did not counterbalance pen order; the lighter pen was used on the first day, and the heavier pen was used on the second day of testing. Here, we either switched or repeated tool type across groups to see whether use of the previous tool has an effect on performance using the current tool. If participants were modifying a single internal model, used to represent this general type of tool movement, interference would be expected for groups that switched tools. If the effect of each tool's unique dynamics was instead represented by a separate internal model, then tool switching should not result in interference.

Finally, we investigated how knowledge is generalized across different tasks by examining performance in both a horizontal and vertical pointing task. Generalization is the process by which knowledge or skills acquired in one situation can be applied to a different situation. By examining how motor execution and motor imagery transfer across different tools and tasks, we can better understand at what level the acquired skills are being represented. If the skills are being represented at the level of commands to the muscles, then there should be a cost when switching to another task configuration. If the skills are being represented at a higher level, then there should be no real cost of switching to a new task configuration (i.e., generalization). Here, we vary the orientation of the stimuli (horizontal vs. vertical) as a within-group variable, which alters the type of movement required to complete the pointing task and examine generalization by checking to see whether there is a cost of switching from performing a horizontal version of the pointing task (wrist abduction/adduction) to a vertical version of the pointing task (wrist extension/flexion). To perform the vertical task, participants cannot simply use motor memory of the horizontal movement, as the vertical task requires using different muscles. If performance decreases following the switch, we will infer that generalization did not occur. If performance does not decrease following the switch, we will infer that generalization has occurred, and that the skills are being represented at a higher level.

Method

Participants

Thirty-eight participants (15 men and 23 women) aged 18–25 years (mean = 19.5) performed a series of simple pointing tasks. All participants reported having normal or corrected-to-normal vision and were recruited through online advertisement. All participants self-reported right hand dominance. The University of Oregon's Institution Review Board (IRB) approved the protocol, and all participants signed a consent form to participate in the study.

Apparatus and design

A pointing task was used to measure MTs for real and imagined movements using a regular felt tip Sharpie pen (Fig. 1a) and two weighted tools that were top- (Fig. 1b) or bottom-heavy (Fig. 1c) in two different tapping conditions: horizontal (Fig. 2a) and vertical (Fig. 2b). The regular Sharpie pen was 14.2 cm long and weighed 0.03 kg. The bottom-heavy and top-heavy tools were approximately 28 cm in length, and each had a fine-tip Sharpie pen attached to the end. The bottom-heavy tool had a 0.18 kg weight attached 17.5 cm away from the base (non-tapping end), and the top-heavy tool had a 0.09 kg weight attached 2.4 cm away from the base. Participants gripped the tools just as they would a regular pen. The task and its procedure for administration were modified from that used by Sirigu et al. (1995, 1996) and Danckert et al. (2002), and all conditions were counterbalanced over participants. To summarize, we varied *movement condition*: real or imagined, *tool type*: regular pen (control condition), top-heavy pen, or bottom-heavy pen, and *tapping task*: horizontal or vertical. We also manipulated *tool order*, which will be discussed later.

On each trial, participants were given an 8.5″ × 11″ paper sheet marked with a 80-mm black vertical line as well as a square target box to the left of the vertical line with its closet edge 30 mm away and centered in relation to the line. Equidistant from the vertical line and target box was a small fixation dot. Five different target widths were used (1.25, 2.50, 5.00, 10.00, and 20.00 mm), and participants performed two trials for each target width. Based on Fitts' law, the 1.25 mm width would result in a high ID, whereas the 20.00 mm width would result in a low ID, meaning that it should be the easiest. MT should increase as a linear function of the ID.

Real movement conditions—For the motor execution (real movement) trials, one trial was defined as the time for the participant to tap between the vertical line and somewhere within the perimeter of the square target box five times. Each tap in the square and return to any point right of the vertical line was considered one complete cycle. Participants completed five cycles of these back and forth movements, always ending at the cross on the vertical line, for each target width trial. Each width was presented twice in a Latin-square counterbalanced order. Participants were instructed to stare at the fixation point and not move their eyes. Two experimenters used stopwatches to independently record the time to complete each trial, and durations were averaged. The pen was held in the right hand, and participants were instructed to perform the task as quickly and accurately as possible. Participants were also instructed to keep their forearm stationary during the tasks, only moving their hand and wrist. The timers were started the moment the experimenter said "begin" and ended the moment the participant returned the pen or tool to the starting position (the cross on the vertical line) after executing five cycles of tapping between the line and the target. Trials in which the participant tapped the pen outside the perimeter of the target square were repeated. Participants were then reminded to perform the task as quickly and accurately as possible, and to slow down if it allowed them to complete the task accurately.

Imagined movement conditions—For the motor imagery (imagined movement) trials, participants were instructed to consciously think about performing the motor task while voluntarily inhibiting themselves from actually executing it. That is, participants imagined performing the same pointing task without physically tapping between the box and vertical line. Instead, the participants' hands remained fixed at the starting position and with their eyes staring at the fixation point. When instructed to "begin," participants simply lifted the pen and then returned it to the starting position after *imagining* their hand moving to complete the exact pointing task in the motor execution condition described above. As before, experimenters started the timers immediately after instructing the participant to "begin." Although no task-related movement occurred, timers were stopped the moment participants reported completion of the simulated task by returning the pen or tool to the starting position.

Before the trials began, experimenters read participants an explanation of motor imagery to make sure they understood what to do and also to distinguish motor imagery from visual imagery. Furthermore, motor imagery trials occurred before motor execution trials to ensure participants were not simply memorizing the time required to complete the five cycles for each respective box size.

Participants were also given four practice trials of target widths (1.40, 3.50, 4.50, and 5.50 mm) to perform with the regular pen. A distance of 35 mm separated the square target and vertical line in the practice trials. The target widths and distance between the target and vertical line in the practice trials differed from the experimental conditions to avoid the possibility of participants memorizing real duration times and using this knowledge as a basis for performing the imagined exercises in the experimental trials. Seven participants performed a fifth practice trial because of difficulties performing the first four practice trials accurately.

All 38 participants were placed in one of four counterbalanced groups (BTbt, BTtb, TBtb, and TBbt), reflecting the order in which they performed the pointing task with the weighted pens in both the horizontal and vertical paradigms. For each paradigm, half of the subjects performed the weighted Fitts' task with the bottom-heavy stylus; the other half performed this task first with the top-heavy stylus. The upper case "B" and "T" letters indicate pen order in the horizontal paradigm; the lower case "b" and "t" letters indicate pen order in the vertical paradigm. Importantly, two groups used the same tool in succession from one task to another (i.e., Top-heavy tool followed by top-heavy tool—Tt; and Bottom-heavy tool followed by bottom-heavy tool—Bb). The other two groups first used one tool and then used the other tool, switching tools between tasks (i.e., Top-heavy tool followed by bottom-heavy tool—Tb and Bottom-heavy tool followed by top-heavy tool—Bt).

Order of experimental procedure

The experimental order is detailed in Table 1. Note that for each task, motor imagery trials preceded motor execution trials to prevent participants from attempting to use a timing memorization strategy to perform the task. In order to acquaint participants with the tools, a tracing and tapping task was given prior to each part below where tools were involved (Table 1, 2a–3b).

Prior to the beginning of Parts 2a, 2b, 3a, and 3b (Table 1), participants performed a brief tracing and tapping task to become familiar with the bottom-heavy and/or top-heavy tools. The task involved tracing shapes (star, triangle, rectangle, and square) in a clockwise order, numbered one through four, repeating all four shapes counterclockwise in the reverse order. Then participants tapped in the small circles along the perimeter of various shapes, repeating in reverse order, as in the tracing task. Participants were instructed to perform the tracing and tapping task as quickly and accurately as possible, although they were not being timed. Even in instances where pen types between Parts 2b and 3a (Table 1) did not change (counterbalanced groups BTtb and TBbt), participants still performed the tracing and tapping task.

Not every participant repeated the standard pointing task in Part 4 (Table 1) as this task was added to the experiment protocol after examining the first 11 participants. Part 4 was incorporated to evaluate potential practice effects associated with repeating the same pointing task (i.e., if there was a general improvement over time).

Data analysis

Each participant's mean movement, or imagery, duration was calculated for target width (the average of two trials per target width) and organized according to the movement (real or imagined), tool (top-heavy, bottom-heavy, and regular pen), and task (horizontal and vertical) conditions. To determine whether real and imagined movements conformed to Fitts' law under each condition, the group mean MT was plotted against the ID measure. Recall from the introduction that we are using Fitts' law (Eqs. 1 and 2) to express target width and movement amplitude (distance between the target and starting position, which was a constant in this experiment) as an index of difficulty (Eq. 2). Linear fits to the data were calculated and plotted (Eq. 1). The data were then subjected to various statistical analyses as detailed in the Results section. Data collected from participants 13 and 38 were completely omitted from the experimental analysis, as over half the recorded imagery and real movement values extended beyond a 1.5 interquartile range (IQR).

Results

Overall speed-accuracy relationships

Consistent with past reports (Sirigu et al. 1995; Decety and Jeannerod 1996; Sirigu et al. 1996; Cerritelli et al. 2000; Choudhury et al. 2007), the speed-accuracy trade-off for both real and imagined movements conformed to Fitts' law in all experimental conditions, as demonstrated by the linear relationship between MT and ID (Fig. 3). Furthermore, imagined and real movement data for all experimental conditions were highly correlated (Table 2), indicating that imagined movements are constrained by the same laws as real movements, even when novel tools are used. Linear regressions of MT as a function of ID and the corresponding R^2 values are listed in Table 3 to show how well our data conform to Fitts' law.

Imagined versus real movements

To investigate whether imagined and real movements conformed to Fitts' law, mean MTs were plotted against the ID measure. Figure 3 (all imagined and real conditions shown) and Fig. 4 (main effect of imagined vs. real movement) reveal a greater separation between imagined and real MTs at the higher indexes of difficulty (the smaller and more difficult target box widths). This was supported by a significant interaction between movement type (imagined vs. real) and ID in a 2 × 5 repeated measures ANOVA ($F(4, 148) = 85.603$, $p < 0.001$, partial $\eta^2 = 0.698$). Furthermore, the overall slope for imagined movements is smaller than the slope for real movements ($t(37) = 10.962$, $p < 0.001$), suggesting that participants underestimated the time required to perform the task as it became more difficult (i.e., higher IDs). Figure 3 also shows that real movements took longer for the top-heavy tool compared to the bottom-heavy tool. Next, we focus on this difference between durations for top- versus bottom-heavy tools.

Effects of weighted tools

Figure 5 shows the relationship between real and imagined movements for the two tool types, as well as for the regular pen control condition. The solid black unity line (slope = 1 or $y = x$) represents what performance should look like if imagined movements were veridical (i.e., identical to real movements). The fact that the slopes for imagined versus real movements were all less than 1 indicates that, in the imagery conditions, participants consistently underestimated the time required to perform the movements. As noted previously in Figs. 3 and 4, this was especially true for smaller target width (higher ID) trials. To quantify this, we analyzed slopes for the least squares functions describing the relationship between imagined versus real movements for the regular pen and the top- and bottom-heavy pens for each participant. Group mean performances according to tool type, collapsed across task orientation, are illustrated in Fig. 5. Both bottom- and top-heavy tools altered the relationship between imagery and execution when compared to the regular pen (F (2, 74) = 7.246, $p = 0.001$, partial $\eta^2 = 0.164$). Both tools differed significantly from the regular pen (Bottom-heavy vs. regular mean difference = 0.137, $p = 0.010$; Top-heavy vs. regular mean difference = 0.162, $p = 0.002$). However, the difference between the two weighted tools with regard to their impact on the imagined versus real movement relationship was not significant.

We found that adding weight to the tool significantly impacted real MTs, but not duration estimates based on imagery. When comparing real and imagined performance for the bottom- and top-heavy tools, we found that the tool affected real but not imagined MTs, as shown by a significant interaction in a 2 × 2 repeated measures ANOVA ($F(1, 37) = 12.669$, $p = 0.001$, partial $\eta^2 = 0.255$). Physically performing the task took longer with a top-heavy tool than with a bottom-heavy tool ($F(1, 37) = 18.450$, $p < 0.001$, partial $\eta^2 = 0.333$), while imagined performance was unaffected by tool type. By introducing two novel tools with different dynamics, we demonstrate that internal movement representations for individual tools, though distinguishable via execution, are somewhat imprecise.

Effect of tool order

Recall that the upper case “B” (bottom-heavy) and “T” (top-heavy) letters indicate pen order in the horizontal paradigm, and the lower case “b” (bottom-heavy) and “t” (top-heavy) letters indicate pen order in the vertical paradigm. Figure 6 shows the real and imagined mean MTs for each of the four groups (BTbt, BTtb, TBtb, and TBbt) reflecting the order in which they performed the tasks. Critical here are the 2nd and 3rd letters in these sequences, as they indicate the tool that is being used before and after switching between horizontal and vertical versions of the tasks. Following the switch from the horizontal to the vertical task, which we abbreviate using the middle two letters, participants in tool order groups Bb and Tb were currently using the bottom-heavy tool, and those in Tt and Bt were currently using the top-heavy tool.

To examine whether participants’ performance using the current tool was affected by the use of a previous tool, we performed a 2 (movement type) × 2 (current tool) × 2 (previous tool) ANOVA. A comparison of the effect of current tool would examine tool order groups Bb and Tb versus Tt and Bt, whereas a comparison of the effects of previous tool would examine tool order groups Bb and Bt versus Tt and Tb, and an interaction crosses these two comparisons to see whether the effects of the previous tool (T) on current tool (t versus b) is different from the effects of previous tool (B) on current tool (t versus b).

In contrast to what might be expected if a single internal model was being modified to represent movements using both tools, there was no significant interaction between current tool and previous tool ($F(1, 34) = 1.076$, $p = 0.306$), which suggests that use of the previous tool did not interfere with use of the current tool. If the groups that switched tools (Bt, Tb) performed worse than the groups that did not switch (Bb, Tt), then we can conclude that switching tools interfered with performance, suggesting that a single internal model is being modified. If there was no difference between groups, then tool switching did not interfere with performance, suggesting that separate models might exist for each individual tool’s effect on movements. Our data support the latter hypothesis. However, based on our finding that imagined MTs did not discriminate between top- and bottom-heavy tools, it could also be the case that neither tool's effect on movement dynamics was precisely represented and, therefore, did not cause switching interference.

Effects of task orientation

A 2 × 2 repeated measures ANOVA investigating real and imagined mean MT between the horizontal and vertical tasks shows a significant interaction between movement type and task ($F(1, 37) = 11.417$, $p = 0.002$). Specifically, participants' real movements remained relatively stable across tasks, but their imagined MTs became more similar to real MTs (i.e., longer) in the vertical task, as shown in Fig. 7. Because the horizontal task always preceded the vertical task, changes in imagined movement performance could be attributed to an order or practice effect. This trend also exists when observing mean MT of the tasks in the order in which they were performed. Figure 8 shows how the slopes for imagined versus real mean MTs change over time. In other words, there is learning taking place for imagined movements to become more similar to real movements over time.

Practice effects

To explore the possibility of practice effects further, we analyzed the data while taking task order into account (i.e., first horizontal, second horizontal, first vertical, second vertical) with a 2 × 4 repeated measures ANOVA. A significant movement type by order interaction indicates that real and imagined movements are impacted differently by a change in the task orientation, $F(3, 111) = 5.045$, $p = 0.003$. We conducted one-way repeated measures ANOVAs for both real and imagined movements to explore the effect of order for each condition. There was no effect of order for real movements, $F(3, 111) = 1.674$, $p = 0.177$, but there was an effect of order for imagined movements, $F(3, 111) = 7.625$, $p < 0.001$, $\eta^2 = 0.171$. In summary, the difference in duration between the horizontal and vertical tasks can be explained by an order effect, which shows that imagined movements become more similar to real movements over time.

Discussion

Previous studies have demonstrated that real and imagined movements conform to the speed-accuracy relationship described by Fitts' law. This has been interpreted as evidence that motor imagery and execution involve shared internal representations, or models. However, little work has been done to determine whether imagery, like motor control, is influenced by the introduction of a tool or novel object. The current experiment provides a strong test of the hypothesis that these two tasks are similarly affected by looking at how newly acquired tool-use skills are represented and expressed in imagery versus real movements. The novel tools examined in this experiment were designed with weights placed at the top and bottom of two different pens (Fig. 1b, c) to study the effects of altered tool dynamics on internal representations underlying motor imagery and execution. We found that durations of both real and imagined movements involving the unweighted pen, bottom-heavy tool, and top-heavy tool all conformed to Fitts' Law. Likewise, this relationship held for not only the horizontal experiment paradigm (Fig. 2a) previously studied by Sirigu et al. (1996) (that involved wrist abduction/adduction), but also a vertical paradigm (Fig. 2b) (that involved wrist extension/flexion). Overall, these results suggest that imagery and execution may share internal representations, but that imagery is less precise. Execution benefits from feedback control, but imagery does not have access to real-time sensory feedback.

The relationship between imagery and execution for novel tool use

Plotting a participant's imagined versus real motor movement is one way to represent the accuracy of a participant's mentally simulated movements. The unity line ($y = x$) reflects a perfect correlation between real and imagined movements. We hypothesized that an individual's internal representation of movements with a tool would be represented by alterations in imagined MTs. Given the sensorimotor feedback each participant received during the tracing task prior to each experimental condition, we supposed that the tracing practice would provide a basis for predictive (i.e., forward) modeling of the tool's impact on performance during the imagined movement exercises. Although performance with the tools significantly differed from those with the regular pen in terms of real versus imagined movement, the durations for performance with the novel tools did not significantly differ from each other. The impact that the tools have on real but not imagined movement suggests that the internal model of the limb-tool system is not refined enough to simulate the modest differences between the effects of the two tools on MT. Moreover, though the subtle differences in dynamics between the two tools have an effect on real movement, these differences are not observed in imagined movement performance. This finding was somewhat surprising given that 32 out of 38 participants self-reported that the top-heavy tool was more difficult to control than the bottom-heavy tool. That is, even though they clearly perceive a difference, and this is reflected in overt performance, it is not captured in their internal representation of the limb-tool system. These results are consistent with previous studies showing that the addition of weight differentially impacts the MTs for real and imagined movements, even though both real and imagined movements with and without weighted tools conform to Fitts' law (Decety et al. 1989; Cerritelli et al. 2000; Wilson et al. 2001). This finding is consistent with the view that the veridicality of motor imagery is dependent upon task demands (Rodriguez et al. 2008; Rodriguez et al. 2009). Specifically, we find that differences between execution and imagery emerge when tasks demand that participants represent high precision movements and/or subtle changes to system properties, in our case created by differentially manipulating tool dynamics. Such departures may not emerge with coarser measurements, simpler tasks, or larger differences in tool properties.

No cost of switching tools

If participants were modifying a single internal model, used to represent this general type of tool movement, interference should have been expected for groups that switched tools between the second horizontal and the first vertical tasks. If the effects of the dynamics of each tool were, instead, being represented by a separate internal model, then tool switching should not have resulted in interference. We also hypothesized that interference in learning would occur in tool order groups that switched tool types between the second horizontal and the first vertical tasks; however, the data suggest that movements with the previous tool have little to no impact on one's performance using the current tool. This was surprising given the advantage one would seemingly have if they used the same tool type consecutively when transferring between the horizontal to the vertical tapping paradigms.

Generalization across tasks

Here we characterize generalization as speed of performance, or the time required to complete the task. If generalization—the ability to transfer knowledge across tasks—did not occur, we would expect MTs to increase after switching tasks. On the other hand, if generalization did occur, participants should not get slower when switching from the horizontal to the vertical task. Overall mean real MTs remained stable over time, even when switching between the horizontal and vertical tasks, suggesting generalization across tasks. In contrast, imagined MTs became more similar to real MTs over time. Imagined MTs were initially faster than real MTs, since participants tended to underestimate the time it would actually take to perform the task. Over time, and across tasks, imagined movements began to approximate real movements. Although we are unable to claim that generalization occurred for imagined movements, we believe that participants improved in their ability to forward model or predict the time required to complete the task. We report this as a novel finding, since studies have traditionally not examined how imagery performance changes over time.

Because we suspected that imagery might be improving over time or with practice, we added a second Fitts' task to be performed with the regular pen at the end of the study. Improved imagery with time is further supported by imagined MTs that more closely conform to real MTs in the second regular pen task. Although calculated with a smaller sample size ($n = 30$), the slope of imagined versus real movement performance in the second regular pen task more closely conforms to the unity line than does the slope of a regular pen during the first set of trials.

In view of the fact that imagery seems to improve over time or with practice even for the regular pen, which was not a novel tool, subsequent research involving manipulation of the length of training intervals is recommended. To more clearly understand how internal movement representations are formed in response to the introduction of a novel tool, future studies investigating this question should consider providing participants more extended opportunities to gain familiarity with the tool's dynamics, such as providing a longer within-experiment training period or having them use a novel tool for an extended period prior to testing. Furthermore, a more varied array of tools with different functional dynamics should be investigated.

Most studies investigating motor imagery in pointing tasks have not addressed the real possibility and tendency for participants to move their eyes between the target and starting position as a way of simulating the time required to complete the task. This experiment aimed to prohibit this strategy by placing a small fixation dot between the square target and starting position, and participants were asked to fixate at the dot during both imagined and real movement exercises. Previous experiments made no attempt to control fixation. However, it should be noted that subjects reported that maintaining fixation during the task was difficult. Future studies examining motor imagery should investigate whether eye movement plays a role in forming an internal representation of pointing tasks.

Conclusion

Here we found that the speed-accuracy relationship described by Fitts' Law holds across both execution and mental simulation (motor imagery) of movements involving different tools and tasks. This finding extends previous applications of Fitts' law to include both the real and imagined use of novel tools. This is critical because many, if not most, of our everyday manual activities involve the manipulation of tools. Furthermore, we did find that there was an adjustment in imagery times in response to the two weighted tools compared to the regular pen. This indicates that even relatively brief exposure to the properties of a novel tool can be sufficient to influence the internal representation of the tool-limb system and provides a basis for future studies. However, it should be emphasized that this representation is still relatively coarse, given that differences between the top- and bottom-heavy tools were evident for real but not for imagined movements.

Because performance was not significantly affected by switching between the horizontal and vertical tasks, we conclude that generalization occurred for both motor imagery and execution. However, generalization in motor imagery is obscured by the fact that there was a large, unexpected improvement in motor imagery performance over time.

Though motor imagery training has been used to try to help patients with physical or neurological injury regain some motor function (Jackson et al. 2001; Johnson-Frey 2004; Lotze and Halsband 2006; Sharma et al. 2006; Cramer et al. 2007; Page et al. 2007) and to improve motor performance in sports (Feltz and Landers 1983; Yue and Cole 1992; Driskell et al. 1994), the present study raises the issue of whether imagined movements are robust with respect to physical dynamics and prevailing task demands. Our work highlights the need to vary the task and conditions under which imagery and execution are performed, especially under conditions where learning is critical (i.e., going beyond movements of the natural limbs and altering the task layout over the course of the experiment). If movements are not precisely represented during imagery, such as when using two different tools, this may reduce the overall impact of such a technique on simulating the same neural processes associated with real movement, potentially limiting its practical use for rehabilitation and sports training purposes.

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Fig. 1.
a Regular pen (non-weighted), **b** top-heavy tool—with weight positioned at the top, **c** bottom-heavy tool—with weight positioned at the bottom

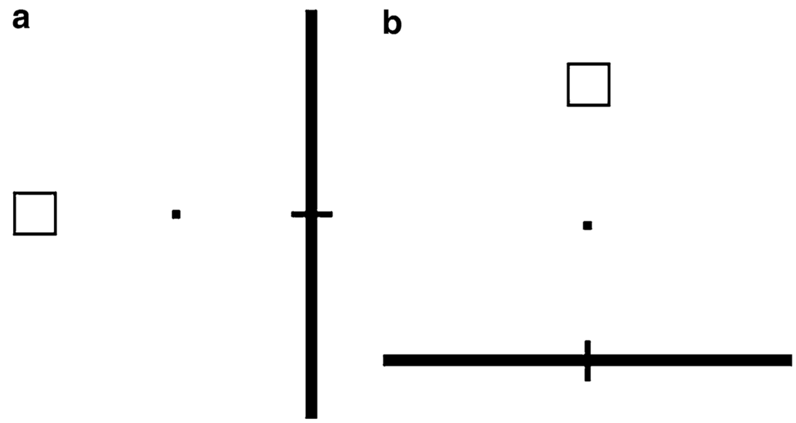

Fig. 2.

a *Horizontal task*: participants fixated center dot while physically tapping or imagining tapping horizontally from the line to the target box for five cycles. Five different box widths were examined: 1.25, 2.50, 5.00, 10.00, and 20.00 mm^2, **b** *vertical task*: participants fixated center dot while physically tapping or imagining tapping vertically from the line to the target box for five cycles. Five different box widths were examined: 1.25, 2.50, 5.00, 10.00, and 20.00 mm^2

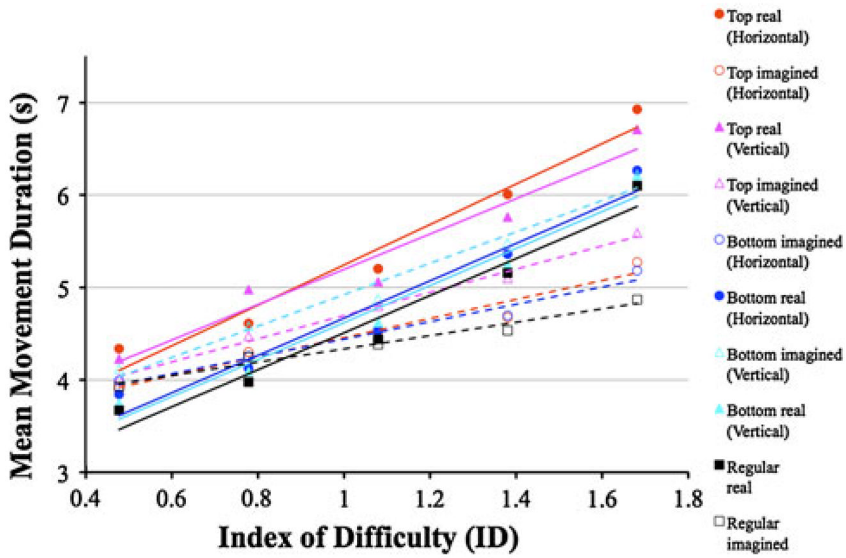

Fig. 3.

Mean MT plotted against ID for all experimental conditions. Linear regressions plotted with *solid lines* denote real movements, and *dashed lines* denote imagined movements. The linear relationship between duration and ID (i.e., Fitts' law) holds across all experimental conditions: top-heavy and bottom-heavy tools, and horizontal and vertical paradigms, for both real and imagined trials

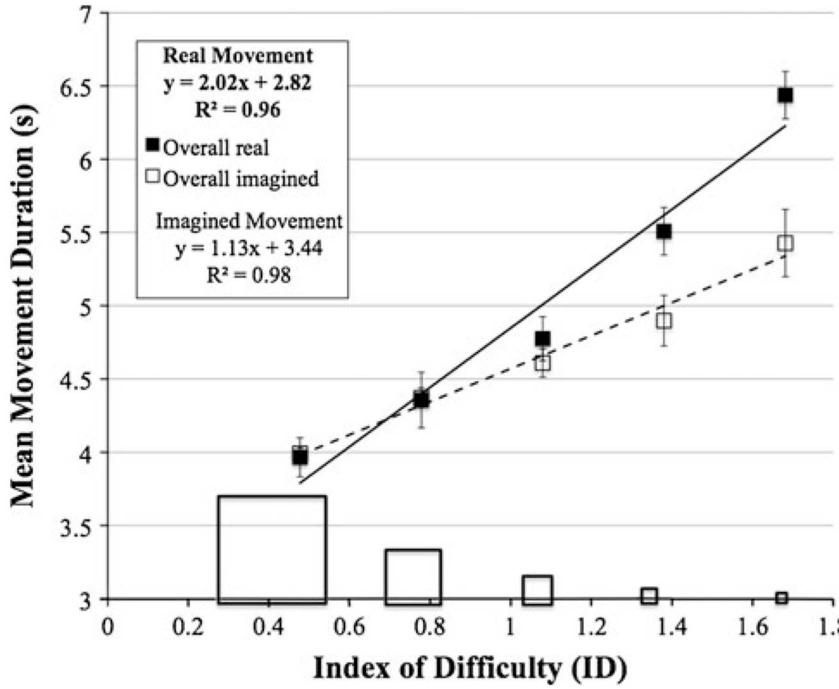

Fig. 4.

Mean MT (±SE) for imagined versus real movements collapsed across tools and tasks as a function of ID as calculated by Fitts' law. Target box size is depicted above the corresponding ID. Note that ID increases as the box size decreases. Linear regressions for real (*bold*) and imagined data are shown on the graph along with their corresponding R^2 values. High R^2 values indicate that the relationship between ID and MT is highly linear, providing strong evidence that both imagined and real movements adhere to Fitts' law for all experimental conditions. The slope for real movements is steeper than the slope for imagined movements, such that participants underestimate imagined MTs as the ID increases

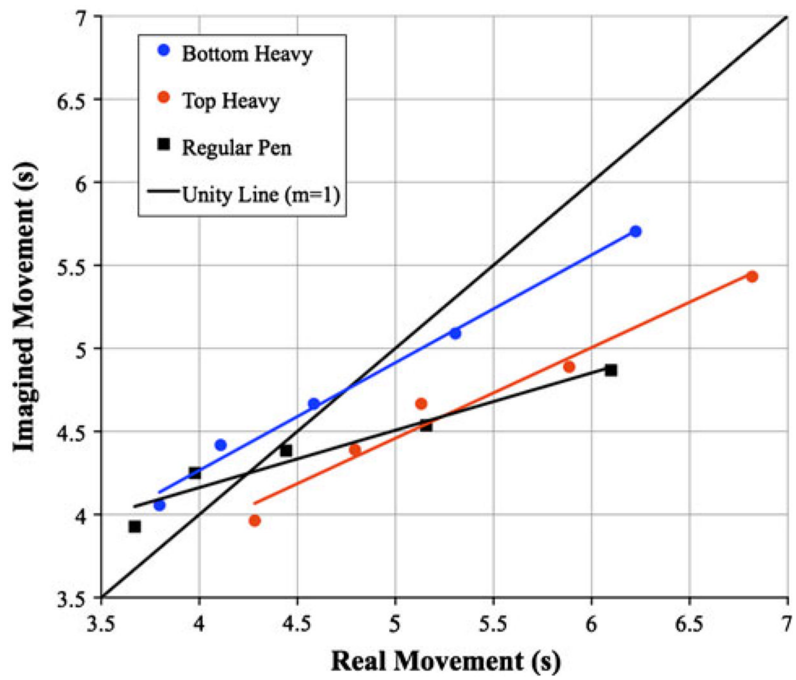

Fig. 5.

Comparison of imagined (*y* axis) versus real (*x* axis) mean MTs collapsed across *horizontal* and *vertical tasks* to examine the main effect of tool type. The unity line of $y = x$ has a slope of 1 and represents what would be a perfect correlation between real and imagined MTs. Slopes for bottom-heavy and top-heavy tools were closer to 1 than the slope for the regular pen, such that more veridical imagined versus real movement performance was observed following the introduction of a novel tool (whether top-heavy or bottom-heavy)

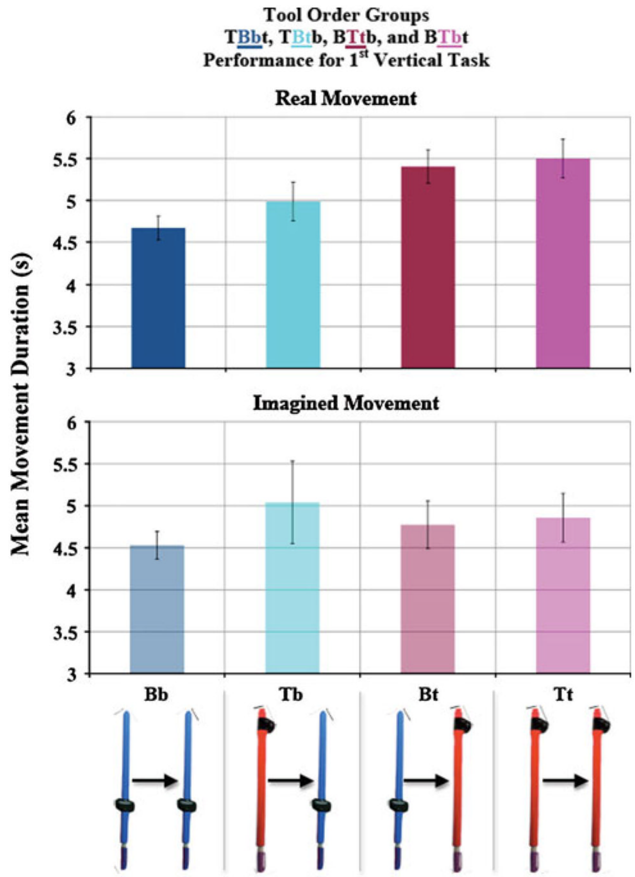

Fig. 6.

Real and imagined mean MTs collapsed across target widths in the first vertical task for each of the four tool order groups (Bb, Bt, Tt, and Tb). The *reddish* colors (Bt and Tt) represent those currently performing the top-heavy task, while the *bluish* colors (Bb and Tb) represent those currently performing the bottom-heavy task. In the current task, top-heavy tools (Tt, Bt) resulted in longer mean durations than bottom-heavy tools (Bb, Tb) for real movement, but imagined MTs were unaffected. However, the previously used tool had no significant effect on either imagined or real performance (color figure online)

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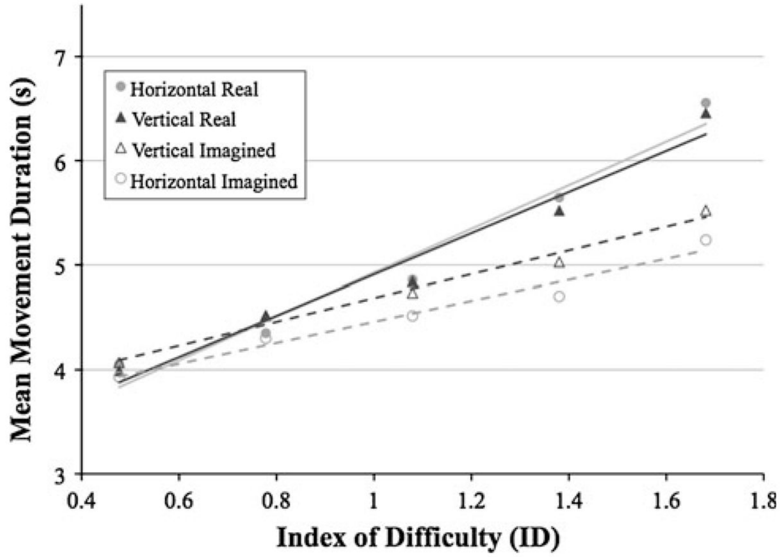

Fig. 7.

Comparison of horizontal versus vertical mean MT as a function of ID for real and imagined conditions collapsed across tool type. Real movement performance for the vertical and horizontal tasks is similar, whereas imagined MTs differ across tasks. Imagined MTs for the vertical task were more closely aligned with real MTs than for the horizontal task

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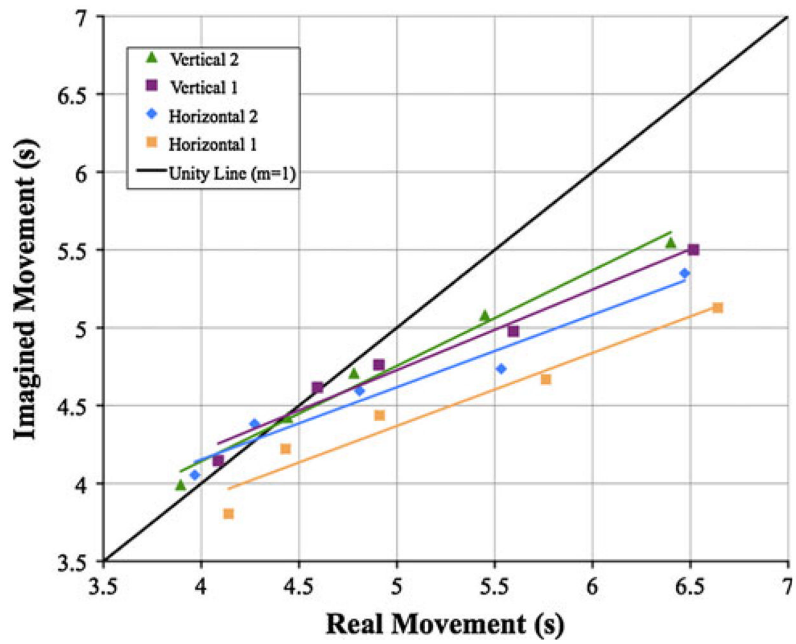

Fig. 8.

Comparison of imagined versus real mean MTs according to order of performance. Recall that tasks were performed in the following order: horizontal 1, horizontal 2, vertical 1, vertical 2. Real mean MTs remain fairly stable across time. However, as the experiment progressed, imagined MTs approached real MTs (i.e., moved closer to the unity line)

Table 1

Timeline of experiment

	Experimental task
Part 1	*Practice trials with regular pen*
	Standard horizontal task with regular pen
	Participants performed a horizontal pointing task (Fig. 2a), as in Sirigu et al. (1996), using a regular, non-weighted Sharpie pen (Fig. 1a). Imagery trials preceded execution trials
Part 2a	*Tracing and tapping task*
	Horizontal task with bottom-heavy or top-heavy tool
	Participants performed the horizontal pointing task (Fig. 2a) using a top-heavy (Fig. 1b) or bottom-heavy tool (Fig. 1c). Half of the participants performed the task first using the top-heavy pen (T); the other half first used the bottom-heavy pen (B). Imagery trials preceded execution trials
Part 2b	*Tracing and tapping task*
	Horizontal task with other tool
Part 3a	*Tracing and tapping task*
	Vertical task with bottom-heavy or top-heavy tool
	Participants performed the vertical pointing task (Fig. 2b) using a top-heavy tool (Fig. 1b) or bottom-heavy tool (Fig. 1c). Half of the participants performed the task first using the top-heavy pen (t); the other half first used the bottom-heavy pen (b). Imagery trials preceded execution trials
Part 3b	*Tracing and tapping task*
	Vertical task with other tool
Part 4	*Repeat standard task*
	Participants repeated Part 1

Table 2

Correlation values between real and imagined MTs in all experimental conditions

Task	Correlation
Regular pen	0.969
Bottom-heavy horizontal	0.989
Top-heavy horizontal	0.968
Bottom-heavy vertical	0.996
Top-heavy vertical	0.981
Regular pen (repeated)	0.985

Table 3

Linear regressions of group mean MT for real and imagined motor sequences for the regular pen, bottom-heavy tool, and top-heavy tool in the horizontal and vertical paradigms

Task	Linear	R^2
Horizontal task		
Regular pen—real	$y = 2.006x + 2.505$	0.96
Regular pen—*imagined*	$y = 0.720x + 3.616$	0.97
Bottom-heavy tool—real	$y = 2.019x + 2.650$	0.95
Bottom-heavy tool—*imagined*	$y = 0.937x + 3.505$	0.97
Top-heavy tool—real	$y = 2.185x + 3.059$	0.96
Top-heavy tool—*imagined*	$y = 1.029x + 3.429$	0.95
Vertical task		
Bottom-heavy tool—real	$y = 2.0025x + 2.619$	0.97
Bottom-heavy tool—*imagined*	$y = 1.698x + 3.225$	0.97
Top-heavy tool—real	$y = 1.910x + 3.287$	0.94
Top-heavy tool—*imagined*	$y = 1.255x + 3.442$	0.99