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To cite this article: James W. Roberts, Robin Owen & Caroline J. Wakefield (07 Jul 2025): Mental Chronometry: Do Imagined Times Merely Relate to Task Duration?, Journal of Motor Behavior, DOI: [10.1080/00222895.2025.2525907](https://doi.org/10.1080/00222895.2025.2525907)

To link to this article: <https://doi.org/10.1080/00222895.2025.2525907>



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Published online: 07 Jul 2025.



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# Mental Chronometry: Do Imagined Times Merely Relate to Task Duration?

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**ABSTRACT.** Prolonged movement time as a function of task difficulty (as defined by the Index of Difficulty [ID]) can be equally prevalent within executed and imagined movements — something referred to as the *mental chronometry effect*. This effect has been leveraged as support for *functional equivalence*, where an internal representation can be shared for execution and imagery. However, times tend to rise exponentially more for imagined, compared to executed, movements, which could be attributed to the time spent within a task. Fifteen participants attempted execution and imagery of a reciprocal aiming movement between two targets that assumed different levels of ID (4, 5, 6 bits). They did this either over 3 or 5 cycles of movement to generate short- and long-duration movements, respectively. Mean times and time-ID slope/gradient coefficients revealed that the time within imagery was generally no longer than execution. However, the rise in time as a function of ID tended to be even greater when undertaking 3 compared to 5 cycles within imagery, but not execution. Overall, these findings may counter the suggestion that time spent within imagery is positively related to duration. However, further research is perhaps warranted to help formulate broader recommendations for imagery across different durations.

**Keywords:** equivalence, motor representation, Fitts' Law, manual aiming

## Introduction

**M**otor imagery refers to the mental or internal simulation of movement while devoid of any overt physical movement itself. It is known to be highly effective for the enhanced performance (Ramsey et al., 2008; Wright & Smith, 2009) and (re-)learning (Cabral-Sequeira et al., 2016; Dijkerman et al., 2004; Vogt, 1995) of complex and/or refined motor skills. As a result, much interest surrounds the mechanisms of how motor imagery works (e.g., Bach et al., 2024; Rieger et al., 2024). Indeed, there has been much attention devoted to the concept of *functional equivalence* (Jeannerod, 1994, 1999), where it is suggested that motor imagery utilises the same neural structures and related representations of action as the physical execution of a skilled movement.

One of the main behavioural markers of equivalence has been highlighted by the mental chronometry paradigm, where there is a corresponding time taken to complete imagined and executed movements (Decety et al., 1989; Decety & Jeannerod, 1996; Sirigu et al., 1995, 1996; for a review, see Guillot & Collet, 2005; Guillot

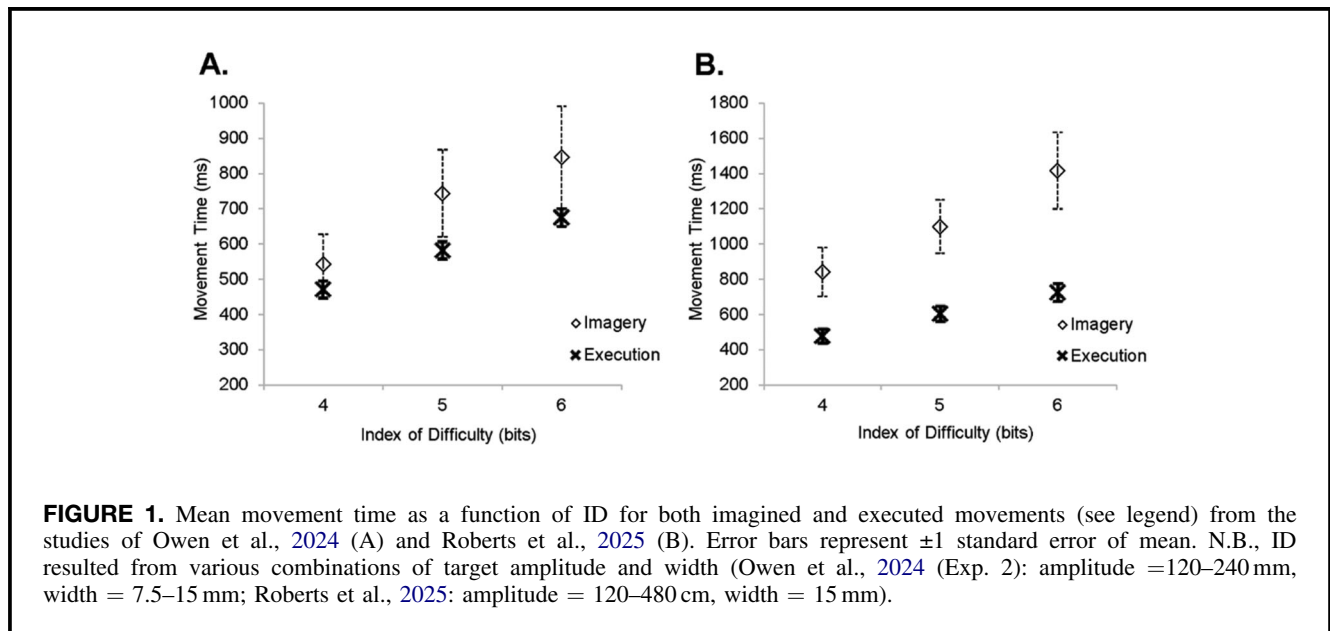
et al., 2012). For example, within a manual aiming task that involves a discrete (i.e., single) or reciprocal (i.e., back-and-forth) movement of the upper-limb to a set target in near space, there tends to be a similar influence of task difficulty on both imagined and executed movements (Cerritelli et al., 2000; Gueugneau et al., 2008; Gueugneau et al., 2017; Owen et al., 2024; Radulescu et al., 2010; Roberts et al., 2019, 2025; Rozand et al., 2015; Slifkin, 2008; Wong et al., 2013; Yoxon, Pacione et al., 2017; Yoxon et al., 2015). In this instance, the task difficulty (as indicated by the Index of Difficulty (ID);  $ID = \log_2(2 \cdot A[\text{amplitude}]/W[\text{width}])$ ) is increased by there being a larger target amplitude and smaller target width, which subsequently increases imagined/executed times ( $MT[\text{movement time}] = a[\text{intercept}] + b[\text{slope/gradient}] \cdot ID$ )—something otherwise referred to as *Fitts' Law* (Fitts, 1954; Fitts & Peterson, 1964).

While the influence of task difficulty on imagined and executed movements is widespread across the literature (for a review, see Guillot et al., 2012), the magnitude or extent of this influence remains somewhat uncertain. Specifically, there are studies indicating that an increase in task difficulty can cause an even greater or exponential rise in the imagined, compared to executed, times (Decety et al., 1989; Cerritelli et al., 2000; Slifkin, 2008; Roberts et al., 2019; Owen et al., 2024; Roberts et al., 2025; see also, Calmels et al., 2006 and Dahm & Sachse, 2025) (for an example, see Figure 1). According to the recently coined *motor-cognitive model* (Glover & Baran, 2017; see also, Glover et al., 2020; Martel & Glover, 2023), these increasing imagined times can be primarily attributed to a failure in the motor representation to adequately simulate the required movement, which then becomes substituted by a time-consuming

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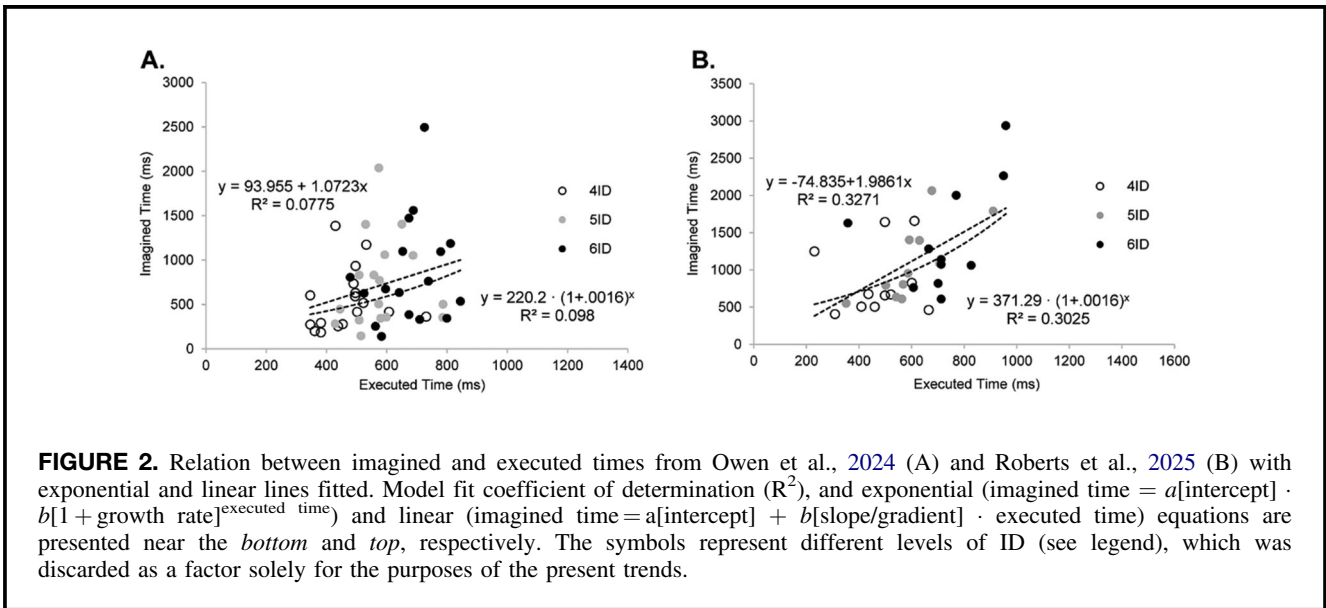


cognitive process that coarsely attempts to generate the image. This suggestion has been separately supported by evidence of how initial task exposure or practice to help refine the representation can cause a decrease in imagined times so they become closer to executed times (Wong et al., 2013; Yoxon, Pacione et al., 2017; Yoxon et al., 2015). In other words, when the representation becomes so refined that there is limited error, then there is no longer a need for any additional cognitive processes, nor a delay in imagined times.

However, it is important to recognise how the suggested influence of task difficulty coincides with changes in duration. In this regard, it could be alternatively argued that the increased imagined times are primarily a feature of scale or time spent within the task. Specifically, if it takes a comparatively long time to physically execute a particular movement, then the imagery of that same movement may take an even longer amount of time to complete. A similar principle has been coined for the relation between spatial distribution and magnitude of force; that is, there tends to be a greater dispersion of movement trajectories following a more forceful impulse (Schmidt et al., 1979; see also, Weber's Law [Weber, 1996]). While there have been related proposals surrounding the influence of task duration on imagined times (see Figure 2 from Guillot et al., 2012; see also, Nalborczyk & Grasso, 2024), there has been a failure to specifically recognise the purported exponential rise in imagined times when undertaking a generally short-duration task, such as the manual aiming that is of interest to the present study ( $< 2$ -s duration per movement). Hence, this study aims to more deeply explore the influence of task duration while being independent of task difficulty.

As a somewhat coarse assessment, we could first explore the co-variation of imagined and executed times independent of Index of Difficulty (ID) from some of our previous datasets involving discrete aiming movements (i.e., non-cyclical) (Owen et al., 2024 [Exp. 2]; Roberts et al., 2025). If the greater increase in imagined times is primarily attributed to the mere scale or task duration, then we would anticipate this increase to unfold mostly for those individuals that tend to generate longer executed times. This trend may be depicted by an exponential and/or linear (with a slope/gradient coefficient  $[b] > 1$ ) relation between imagined and executed times. Upon review, we can observe a somewhat limited exponential and linear relation between imagined and executed times following a small growth /gradient, respectively (see Figure 2B and 2C). Meanwhile, the model fits are either weak, or at best, modest for only one set of the data.

While this observation may lead us to initially suspect a limited role of task duration, further experimentation is warranted, where task duration and difficulty can be systematically controlled (for related manipulations involving reciprocal bimanual movements, see Dahm & Rieger, 2016). With this in mind, it is possible to manipulate the task duration by altering the number of required movements, while retaining the motor control parameters that are dictated by nominal levels of task difficulty. Specifically, we had participants undertake imagery and execution protocols of reciprocal manual aiming for varying periods of time (moving back-and-forth between two targets for either 3 and 5 cycles [6 and 10 segments]) at different levels of difficulty (4–6 bits). If the rise in imagined times is unrelated to task duration and primarily attributed to control parameters, then we



**FIGURE 2.** Relation between imagined and executed times from Owen et al., 2024 (A) and Roberts et al., 2025 (B) with exponential and linear lines fitted. Model fit coefficient of determination ( $R^2$ ), and exponential (imagined time =  $a[\text{intercept}] \cdot b[1 + \text{growth rate}]^{\text{executed time}}$ ) and linear (imagined time =  $a[\text{intercept}] + b[\text{slope/gradient}] \cdot \text{executed time}$ ) equations are presented near the *bottom* and *top*, respectively. The symbols represent different levels of ID (see legend), which was discarded as a factor solely for the purposes of the present trends.

predict that the greater increase in imagined compared to executed times as a function of ID would be independent of the number of movements (i.e., protocol x ID interaction). However, if it is alternatively related to task duration, then we predict that the increase in imagined times would unfold more so for those trials when there is a higher number of movements (i.e., protocol x cycles and/or protocol x ID x cycles).

**Method**

**Participants**

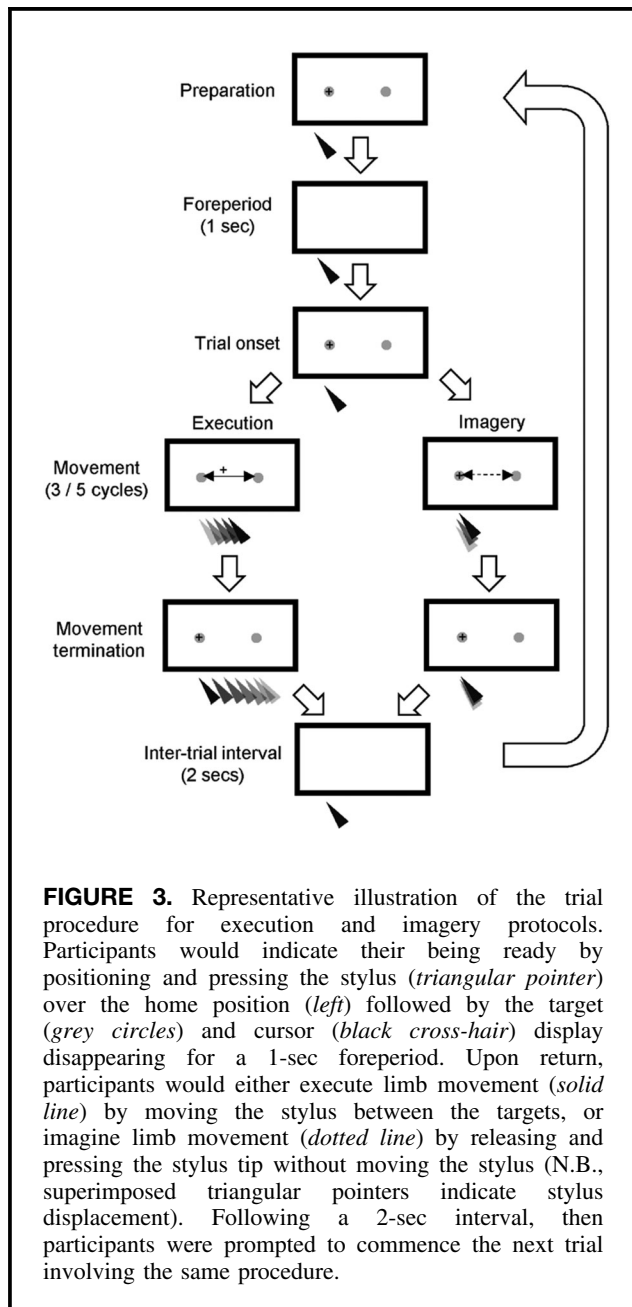
There were 16 participants that volunteered for the study, although one was removed due to a failure to follow the imagery protocol instructions (see later for *Materials and Task*) ( $n=15$ ; age range = 18–38 years, 13 right- and 2 left-hand dominant [self-reported], 9 males and 6 females). An apriori power analysis using G\*Power (v. 3.1.9.4) (Faul et al., 2007) (including the following parameters:  $\eta_p^2 = .14/f = .40$  [large effect size; based on Owen et al., 2024 [Exp. 2] and Roberts et al., 2025],  $\alpha = .05$ ,  $1-\beta = .80$ , and number of measurements = 6 [2 protocol x 3 ID]), estimated a minimum  $n=8$ . Participants pre-experimentally completed the Movement Imagery Questionnaire-Revised (MIQ-R) (Hall & Martin, 1997), and reported a visual ability of  $M=22/28$ ,  $SE=1.49$ , as well as a kinaesthetic ability of  $M=21/28$ ,  $SE=.74$ . The study was designed and conducted in accordance with the 1964 Declaration of Helsinki, and approved by the Liverpool Hope University Research Ethics Committee (Reference: SEL-25022022-007).

**Materials, Task and Procedure**

Movement responses were captured using a stylus pen on a digitising graphics tablet (GTCO Calcomp Drawing Board VI, Scottsdale, AZ) (temporal resolution = 125 Hz [8 ms per frame], spatial resolution = 1000 lines per inch), which remained out of the participants’ sight by placing it underneath a height-adjustable shelving unit. The movement of the stylus was represented as a black cross-hair cursor (8 mm length x 1-mm thickness) over a white background displayed on a CRT monitor (temporal resolution = 85 Hz, spatial resolution = 1280 x 1024 pix, physical size = 310-mm width x 230-mm height), which was placed in front of the participants at eye level (1:1 movement-to-stimulus mapping).

The target stimuli featured two grey circles, which were placed horizontally equidistant with respect to screen centre. The target sizes and amplitudes were determined by select levels of ID, which included 4 (width = 15 mm, amplitude = 120 mm), 5 (width = 11.25 mm, amplitude = 180 mm) and 6 (width = 7.5 mm, amplitude = 240 mm) bits. These stimuli were generated and controlled by Matlab (v. 2018b; The MathWorks Inc., Natick, MA) running Psychtoolbox (v.3.0.11; Pelli, 1997).

A trial commenced when participants placed the stylus pen inside the left target position and pressed down on the tip (see Figure 3). Therein, the screen would go blank (white) for a 1-sec foreperiod. When the cross-hair cursor and targets reappeared, the participants could commence the trial in their own time. Here, participants were instructed to imagine/execute an upper-limb manual reciprocal movement between the two horizontal targets starting from the left as quickly and accurately as possible.



For imagery, participants had to imagine themselves see (first-person perspective) and feel the movement. In order to index their imagined movement, participants would initially release the stylus tip (start) followed by pressing it back down (end) when their imagery of the movement was completed, while physically remaining over the first target (home) for the entire trial. For execution, participants would alternatively move the limb while the stylus tip was in a released state, but remained in contact with the tablet so that it would draw back-and-forth between the targets (i.e., two-dimensional movement), and press back down once they had reached the final target. Following the completion of a trial, the

screen would go blank (white) once again for a 2-sec inter-trial interval before the cross-hair cursor and targets would reappear in preparation for the next trial.

Participants had to generate the imagined/executed movements over 3 or 5 reciprocal movement cycles (6 or 10 individual segments) within separate blocks of trials. These number of cycles were selected because they offered a comparatively coarse separation in task duration, while being consistent with previous mental chronometry research (e.g., Roberts et al., 2019 [4 cycles]; Slifkin, 2008 [3 cycles]; Yoxon et al., 2017 [5 cycles]). Participants were reminded of the required number of cycles at the very start, one-third and two-thirds of the way through each block. There was also a verbal reminder from the experimenter following any rare instance of an incorrect number of cycles. The order of blocks comprising different imagery/execution protocols and number of cycles were counter-balanced between participants.<sup>1</sup> These blocks comprised of 15 trials, including 5 trials for each level of ID, which were presented in a completely random order. Participants had the opportunity to initially practice the imagery and execution protocols prior to the start of the study for the same number of 15 trials, but alternatively with 4 cycles as an intermediate number relative to the test phase of the experiment.

### Data Management and Analysis

For imagined movements, the start and end were taken as the initial release and final press of the stylus tip, respectively. For executed movements, the x- (horizontal) and y-axis (vertical) were first plotted with respect to the outer boundaries of the targets, where the number of segments and errors could be observed and separately recorded. The start of the movement was taken by parsing forward over individual frames from the first frame until the cursor position reached outside the right boundary of the first left target (home). The end of the movement was taken by parsing backward from the last frame until the cursor position returned back into the right boundary of the final left target.

Any trials with an incorrect number of cycles that were executed were removed prior to the analysis (1.04%). The imagined and executed times were taken as the time difference between the start and end of the movement, and averaged across the number of segments (e.g., 7550 ms total time/10 segments [5 cycles] = 755 ms). The individual participant mean movement times were analysed using a three-way repeated-measures Analysis of Variance (ANOVA) including factors of protocol (imagined, executed), ID (4, 5, 6), and cycles (3, 5). In the event of a significant effect featuring the factor of ID, a further linear trend analysis was conducted based on the prediction of Fitts' Law (Fitts, 1954). In the event of a violation in the equal variances assumption (Sphericity), as evaluated

by Mauchly’s test, we used the Huynh-Feldt corrected-value when Epsilon  $\geq .75$ , but the Greenhouse-Geisser corrected-value if otherwise (N.B., original degrees-of-freedom are reported). Based on the mean times, the individual participant slope/gradient was also calculated from a polynomial fit to the degree of 1 (linear) with respect to the different levels of ID. These were then analysed using a two-way repeated-measures ANOVA including factors of protocol and cycles. For each of the inferential statistical analyses, the alpha level was set at  $p < .05$ , while effect sizes were indicated using partial eta squared ( $\eta_p^2$ ).

**Results**

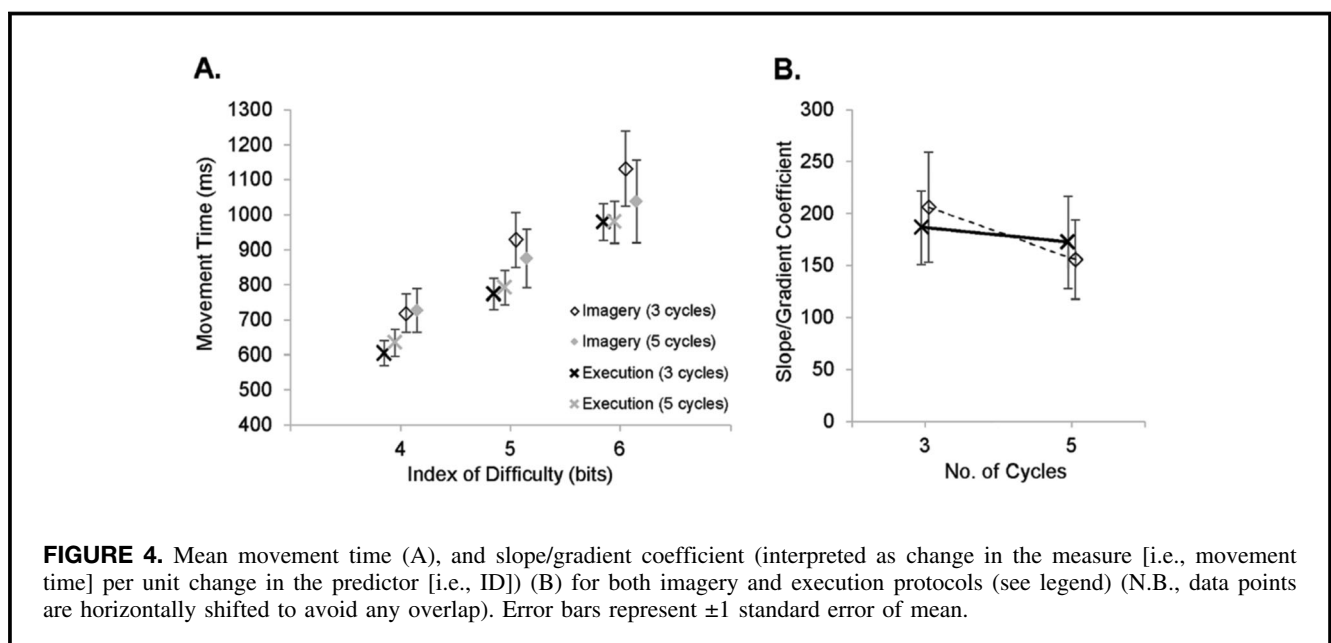
Only 2.63% of movements failed to reach inside the targets during the execution protocol. For movement time, there was no significant main effect of protocol,  $F(1,14) = 3.43, p = .085, \eta_p^2 = .20$ , nor cycles,  $F(1,14) = .23, p = .64, \eta_p^2 = .02$ . However, there was a significant main effect of ID,  $F(2,28) = 71.18, p < .001, \eta_p^2 = .84$ , where there was an increase in movement time following an increase in difficulty,  $F(1,14) = 76.11, p < .001, \eta_p^2 = .85$  (linear) (see Figure 4A). Meanwhile, there was no significant protocol x ID interaction,  $F(2,28) = .06, p = .85, \eta_p^2 < .01$ , although there was a significant ID x cycles interaction,  $F(2,28) = 7.38, p = .008, \eta_p^2 = .35$ , and marginally significant protocol x ID x cycles interaction,  $F(2,28) = 3.33, p = .064, \eta_p^2 = .19$ . Simple effect ANOVAs were subsequently run on each of the protocols (using the original mean square of the error, and related degrees-of-freedom). For execution, there was no significant ID x cycles interaction,  $F(2,28) = .80, p = .46, \eta_p^2 = .07$ . However, for imagery, there was a significant ID x cycles interaction,  $F(2,28) = 9.87, p < .001, \eta_p^2 = .47$ ,

where the increased movement time following increases in ID was even greater for 3 compared to 5 cycles,  $F(1,14) = 15.43, p < .01, \eta_p^2 = .52$  (linear).

For the slope/gradient coefficients, there was no significant main effect of protocol,  $F(1,14) = .002, p = .96, \eta_p^2 < .01$ , although there was a significant main effect of cycles,  $F(1,14) = 10.74, p = .006, \eta_p^2 = .43$ , where there was a greater slope for 3 compared to 5 cycles (i.e., increased rise in movement time following an increase in difficulty) (see Figure 4B). Meanwhile, the protocol x cycles interaction was marginally significant,  $F(1,14) = 3.96, p = .066, \eta_p^2 = .22$ . Simple effect ANOVAs were subsequently run on each protocol (using the original mean square of the error, and related degrees of freedom). For execution, there was no significant main effect of cycles,  $F(1,14) = 1.25, p = .28, \eta_p^2 = .08$ . For imagery, there was a significant main effect of cycles,  $F(1,14) = 15.56, p < .01, \eta_p^2 = .52$ , where there was a greater slope for 3 compared to 5 cycles.

**Discussion**

Following findings of a greater rise in the imagined compared to executed times of aiming movements (Cerritelli et al., 2000; Owen et al., 2024; Roberts et al., 2025), it was suggested that the error within imagined movement times could be scaled to the time spent within the task (for a similar argument, see also, Nalborczyk & Grasso, 2024). As a result, we had participants imagine or execute aiming movements with set target parameters (i.e., amplitude and width) under short and long durations as manipulated by a low (3 cycles) or high (5 cycles) number of movements, respectively. It was predicted that if imagined times were influenced by task duration, then there



would be a greater rise in imagined times following the high (long-duration) compared to low (short-duration) number of movements. The findings indicated that imagined and executed times increased as a function of ID; thus indicating a *mental chronometry effect*. However, the imagined times were not significantly longer than executed times. Further still, the imagined times grew significantly longer alternatively under the 3 compared to 5 cycles of movement.

The mental chronometry effect (slope/gradient coefficient [ $b$ ] mean range = 155–207 ms; taken as the estimated increase in movement time with each single unit or level increase in ID) has been traditionally taken as evidence for the notion of *functional equivalence*, where imagery utilises the same neural representation as physical execution (Jeannerod, 1994, 1999). In support of this conjecture, previous neurobiological studies have indicated that imagery ignites the same neural sites that are also responsible for execution (Hardwick et al., 2018; Krüger et al., 2020), while imagery can elicit increased corticospinal excitability courtesy of transcranial stimulation over the primary motor cortex (M1) (Fadiga et al., 1999; Meers et al., 2020; Wright et al., 2018). That said, the feature of *equivalence* may not exclusively elucidate imagined times following recent evidence of an auxiliary cognitive process that could at least help interpolate or continue the image as movement unfolds (e.g., Glover & Baran, 2017).

Contrary to our original suggestions, imagined times did not overall significantly exceed executed times. Perhaps it should not be too surprising when we consider how the difference between imagined and executed times may be comparatively limited or even reversed depending on the set task (for a review, see Guillot et al., 2012). For example, it has been shown that there are consistently greater imagined compared to executed times when undertaking complex tasks, although we begin to get the reverse effect for more simple tasks (Calmels & Fournier, 2001; Calmels et al., 2006). Nevertheless, the present study was not necessarily concerned with these sorts of mediating factors, but mostly steered by the possibility of the previously reported increases in imagined times being a mere artefact of scale (for a similar suggestion, see Nalborczyk & Grasso, 2024). To elucidate, if imagined times are somewhat erred (e.g., Dahm & Rieger, 2019; Glover & Baran, 2017; Roberts et al., 2020), then this could grow to be even more prevalent for tasks that generally take a longer time to complete. Based on the present findings, we suggest that this possibility is most unlikely, while other alternative factors outside the scope of the present study may serve to influence the magnitude and direction of differences between imagined and executed times (e.g., instructions, imagery type, imagery ability, skill expertise, etc.) (see Moreno-Verdú et al., 2024).

Alternatively, the imagined times actually became significantly longer for the short- (3 cycles) compared to the long-duration trials (5 cycles). Along these lines, it has been previously suggested that, compared to executed times, imagined times tend to become longer within short-duration tasks (i.e., a few seconds), but shorter within long-duration tasks (i.e., several tens of seconds), while assimilating (i.e., ‘isochrony’) within the mid-range duration tasks (Guillot et al., 2012; see also, Guillot & Collet, 2005a, 2005b). Upon reflection, the previously cited examples of a more prolonged imagined time involved a comparatively short-duration discrete aiming task (<2 secs) (Owen et al., 2024; Roberts et al., 2025), as opposed to the presently long-duration reciprocal aiming task (3.5–10 secs). In this regard, there is the possibility that the direction of differences between imagined and executed times may vary over the course of the entire task. For example, consistent with the fore mentioned argument, we might suggest that there be an increased imagined time during the initial phase of imagined compared to executed movements (e.g., 1<sup>st</sup> cycle), although this may be later compensated so that the difference is either no longer or even becomes reversed (e.g., 2<sup>nd</sup>/3<sup>rd</sup> cycle). Perhaps an intuitive way to examine this possibility would be to capture time more frequently at each of the individual movement segments (i.e., multiple key presses) as opposed to restricting it to the movement sequence overall (i.e., start and end key press) (e.g., Calmels & Fournier 2001; Calmels et al., 2006).

In summary, within a reciprocal aiming task (3.5–10 secs), imagined times did not exponentially rise as a function of task duration. Instead, there was some indication that the imagined times were greater for the short- (3 cycles) compared to long-duration (5 cycles) trials. These findings may provide further confidence in any mental chronometry effects by indicating that differences between imagined and executed times are not necessarily related to arbitrary study choices including number of movements, but more importantly, targeted manipulations that directly influence the imagery process (e.g., practice; Yoxon et al., 2015; Yoxon, Pacione et al., 2017). Future research may seek to further qualify the fore mentioned suggestions by more abruptly extending the task duration (e.g., ~30 secs). Herein, we may more appropriately form recommendations for the use of imagery within settings that can accommodate for equivalence, or where it is more likely to unfold (e.g., artistic/rhythmic vs. tumbling/trampoline gymnastics).

### Disclosure Statement

No potential conflict of interest was reported by the authors.

### Note

1. Upon review, our counter-balanced delivery of imagery and execution protocols meant that near half of the participants received imagery before execution (imagery-to-execution;  $n=8$ ), while the other half received execution before imagery (execution-to-imagery;  $n=7$ ). Because prior practice/order of imagery and execution protocols can influence mental chronometry (e.g., Wong et al., 2013; Yoxon, Tremblay et al., Yoxon, Pacione et al., 2017). (e.g., Wong et al., 2013; Yoxon, Tremblay et al., Yoxon, Pacione et al., 2017), we conducted exploratory analyses involving a mixed-design ANOVA that included a new between-measures factor of order (imagery-to-execution, execution-to-imagery), along with the same repeated-measures factors as before. The subsequent report will focus on any statistical effects involving the factor of order. For movement times, there was a mere trend toward a main effect of order,  $F(1,13) = 3.83, p = .072, \eta_p^2 = .23$ , as well as an order x protocol interaction,  $F(1,13) = 4.05, p = .065, \eta_p^2 = .24$ . However, there was a significant order x ID interaction,  $F(2,26) = 6.16, p = .021, \eta_p^2 = .32$ . Further analysis of the slope/gradient coefficients (synonymous with changes across IDs) confirmed a significant main effect of order,  $F(1,13) = 6.72, p = .022, \eta_p^2 = .34$ , which indicated a greater slope for execution-to-imagery compared to imagery-to-execution. There were no further significant interactions involving the factor of order. Please note, these analyses should be treated with caution owing to the small number of participants comprising each of the orders.

### Funding

The author(s) reported there is no funding associated with the work featured in this article.

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Received February 3, 2025

Revised June 6, 2025

Accepted June 19, 2025