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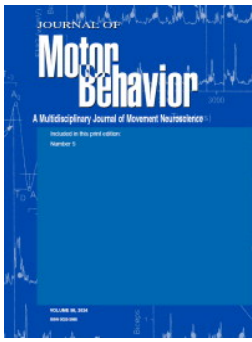
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RESEARCH ARTICLE

Examining the Equivalence Between Imagery and Execution— Does Imagery Comprise the Intended Spatial Trajectory?

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ABSTRACT. The functional equivalence model suggests a common internal representation initiates both imagery and execution. This suggestion is supported by the mental chronometry effect, where there is a positive relation between task difficulty (as defined by the Index of Difficulty; ID) and imagined movement time. The present study extends this logic by examining whether imagery captures the spatial trajectory. Participants were initially tasked with the imagery and execution of a rapid aiming movement under different IDs. These initial attempts were adapted to configure auditory tones at early (25%) and late (75%) intervals for a separate set of imagery trials. If a tone had sounded, participants had to estimate post-trial where their imagined limb would have been located. The findings revealed increases in ID that coincided with increases in imagined and executed movement times. However, participant mean and standard deviation of estimated locations revealed limited differences between the early and late tones. Further inspection revealed some evidence for these estimated locations shifting further along in space following more rapid imagined movements. While equivalence is clearly evident within the temporal domain, there is comparatively little to suggest that this logic extends to the resolution required for simulating the spatial characteristics of movement.

Keywords: mental simulation, internal representation, mental chronometry, Fitts' Law

Introduction

Movement imagery relates to the mental simulation of movement without any overt physical execution of the movement itself. It is often used as an intervention for combating the adverse effects of stress during motor performance (Neil et al., 2006; Ong & Chua, 2015), and the (re-)learning of motor skills (Braun et al., 2013; Gentili et al., 2010; Vogt, 1995). As such, a greater understanding of the processes by which these benefits accrue has been a driving force in movement imagery research.

One such line of research involves the mental chronometry paradigm (for a review, see Guillot & Collet, 2005). Here, individuals imagine themselves completing a movement task, while only being physically able to index the time of the start and the end of the imagined movement. Typically, it has been reported that motor imagery follows a similar speed-accuracy trade-off to that of physical execution, wherein there is a positive relation between the imagined/executed movement times and task difficulty (Decety & Jeannerod, 1995; Gueugneau et al., 2008; Papaxanthis et al., 2002; Radulescu et al., 2010; Roberts et al., 2019; Rozand et al., 2015; Young et al., 2009; see also, Slifkin, 2008). Consequently, it is suggested that

imagery may use the same internal representations as those typically stored and initiated for movement execution; a hallmark of what has come to be known as the functional equivalence model (Jeannerod, 1994, 1999).

At the same time, it has also been highlighted that while imagined and executed movement times similarly increase with increasing levels of difficulty, this increase tends to be even greater for imagined compared to executed movements. This discrepancy does not necessarily refute the notion of functional equivalence entirely, only that imagined and executed movements may begin to differ depending on how much they each rely upon an initial representation. Specifically, if a pre-existing internal representation (e.g., low task difficulty) can be primarily used to fulfil or complete a movement task, then imagery and execution may similarly unfold. However, if the internal representation alone is not suitable (e.g., high task difficulty), and there is the added need to use online sensory feedback to guide the movement (e.g., vision, proprioception), then a separation may begin to emerge between imagined and executed movements because sensory feedback is not necessarily available for imagery as it is for execution. Consequently, as a way to compensate or substitute for the lack of sensory feedback, imagery may recruit more executive resources to consciously generate and monitor an image; hence forming what has come to be known as the motor-cognitive model (Glover & Baran, 2017).

Much of the previously highlighted evidence has involved a measure of movement time. In this regard, we have been somewhat limited to basic temporal characteristics of imagined movements, while potentially assuming

that any effects extend to other elements of movement including the spatial characteristics. Clearly, one reason for this failure is due to the lesser opportunity to capture imagery at a behavioural level given that it typically requires one to be in a rested or dormant state. However, one of our previous studies did alternatively attempt to capture spatial characteristics within imagery by having individuals first reach a target at different criterion times (400/600/800 ms) (i.e., temporally-constrained) (Roberts et al., 2020). Afterward, participants immediately recreated the endpoint location of each of their imagined movements. In keeping with the speed-accuracy trade-off, it was hypothesised that there would be a relation between the within-participant spatial variability and imagined movement times (or velocity when assuming a set distance) (Schmidt et al., 1979). However, there was no such relation as estimates were rather conservatively widespread, while independent of any changes to movement time.

That said, the aforementioned study concluded that these estimates pertained to spatial characteristics that were wholly stochastic in nature. To elucidate, the spatial characteristics of movements additionally feature signal-dependent noise (Meyer et al., 1988; Schmidt et al., 1979) coming from multiple sources across the sensorimotor system (Faisal et al., 2008), which effectively cause the limb to be placed in slightly different positions to what would be initially intended or planned (van Beers, 2009). At this juncture, it is standard for sensory feedback during the movement itself to be used for correcting this error and land on the target (Elliott et al., 2017). Because this error is not necessarily a product of the internal representation that is responsible for movement in the first place, it is reasonable to suspect that maybe imagery would not adequately reflect this sort of information. Therefore, it is still possible that the spatial characteristics pertaining to intended or voluntary sources of movement could be reflected in imagery.

Moreover, due to the so-called noise being evaluated at the end of movements near the target (see Welford, 1968), it is of potential interest to perhaps consider the spatial characteristics that occupy the limb trajectory itself. This interest is somewhat reminiscent of that surrounding the study of imitation and emulation, whereby the movement means or merely the goal of observed actions can be copied by an observer, respectively. The outstanding question in this area revolves around whether individuals correspondingly represent the precise trajectory in addition to the overall goal during action observation (Bisio et al., 2010; Wild et al., 2010, 2011; see also, Bekkering et al., 2000; Hamilton & Grafton, 2006, 2008; Hayes et al., 2016; Roberts et al., 2015). Thus, in a similar vein, we may somehow capture these same spatial characteristics to examine whether the trajectory is also represented within imagery.

The purpose of the present study was twofold; examine whether imagery consists of intended/voluntary sources of the spatial characteristics within movement, and if it conveys the trajectory occupying the near middle portions of the entire movement. With this in mind, we had participants initially execute or imagine aiming movements to targets that assumed varying levels of difficulty within baseline trials. This phase was intended to firstly replicate the corresponding physical and mental chronometry effect, and then also to adapt individual participant imagined movement times for the configuration of auditory cues within a subsequent set of experimental trials. These particular trials once more had participants imagine aiming movements, but with some of the trials featuring an auditory cue at early (25% of the mean imagined movement time at baseline) or late (75% of the mean imagined movement time at baseline) moments of the movement. Following such trials, participants would try to estimate where their imagined limb was in space at the very moment that the previous auditory cue had been presented during that trial (for similar procedures, see Roberts et al., 2020).

Consistent with the plethora of research findings on imagery, we would predict a similar physical and mental chronometry effect, whereby imagined and executed movement times would similarly increase with increasing levels of difficulty. In addition, if movement imagery extends to the representation of the spatial characteristics within a trajectory, then we would predict there to be distinct separation between the post-trial spatial estimates for early and late cues. However, if movement imagery fails to incorporate intended or voluntary sources of the spatial characteristics within movement, then we would predict a rather random distribution of estimates that do not clearly distinguish each of the early and late cues.

METHOD

Participants

An apriori power analysis was initially conducted using G*Power software (version 3.1.9.4; see Faul et al., 2007) including the following parameters: $\alpha = .05$, $1-\beta = .80$, number of measurements = 6 (x2 protocol, x3 ID; see later for *Materials and Task*), $\eta_p^2 = .14$ ($f = .40$). The desired effect size was adapted from recent studies indicating the mental chronometry effect, as well as an interaction with ID (e.g., Glover & Baran, 2017; Roberts et al., 2019; Yoxon, Pacione et al., 2017; Yoxon, Tremblay et al., 2015). The subsequent estimated sample size was $n = 8$, although there were 10 participants (age range = 18-40 years) that agreed to take part in the study. Participants had normal or corrected-to-normal vision, and had no known neurodiverse condition. The study was designed and conducted in accordance with the Declaration of Helsinki (2013), and approved by the local research ethics committee (ref no.: S 15-06-2017 DEL 013).

Materials and Task

Participants stood over an LCD monitor (dimensions $= 47.5 \times 27.0$ cm; temporal resolution $= 75$ Hz; spatial resolution $= 1920 \times 1080$ pixel) that was placed facing upward on top of the inset of a polystyrene box, which was secured to a table using weights inside. The monitor was covered using a fully transparent acrylic sheet with a 2-mm thickness, which acted as the movement surface. Participants were pre-fitted with a thin lycra glove, which had a button micro-switch (Saia-Burgess Electronics, Murten, Switzerland) attached to the underside of the index finger, and a retro-reflective marker attached to the top of the index finger. The micro-switch was connected to an adjacent computer *via* a serial port link, and enabled the capture of temporal events for both calculating movement times and signalling the computer to control the experiment courtesy of a custom-written programme in MATLAB (2018b; MathWorks, Natick, MA). The marker was intended for the measurement of spatial estimates following movement imagery (for details, see later within *Experimental Trials*) courtesy of it being detected by an external motion capture system; that is, the Vicon Vantage (16-megapixel resolution) (Vicon Motion Systems Ltd., Oxford, UK).

Participants had to execute or imagine a discrete aiming movement from left-to-right towards a target as quickly and accurately as possible using their dominant upper-limb. The difficulty of the task was varied according to the Index of Difficulty (ID), which can be calculated by $ID = \log_2(2 \cdot A[amplitude]/W[width])$. This calculus forms an important variable of the linear equation for the estimation of movement time (MT), which can be calculated by $MT = a[intercept] + b[gradient] \cdot ID$); something otherwise referred to as *Fitts' Law* (Fitts, 1954; Fitts & Peterson, 1964). In other words, targets that assume a smaller width and/or longer amplitude compared to a larger width and/or shorter amplitude tend to generate a more prolonged movement time. The target parameters selected for this particular study involved a square width of 15×15 mm, and amplitudes of 12, 24 and 48 cm, which assumed IDs of 4, 5 and 6 bits, respectively.

This task was completed as part of two separate blocks including initial baseline trials followed by a set of experimental trials. The initial baseline trials served two purposes; that is, the replication of physical and mental chronometry as a function of ID, and the identification of participant-specific cue times for the later experimental trials. Meanwhile, the subsequent experimental trials tested the capacity for imagery to simulate spatial trajectories by re-enacting the location of set points.
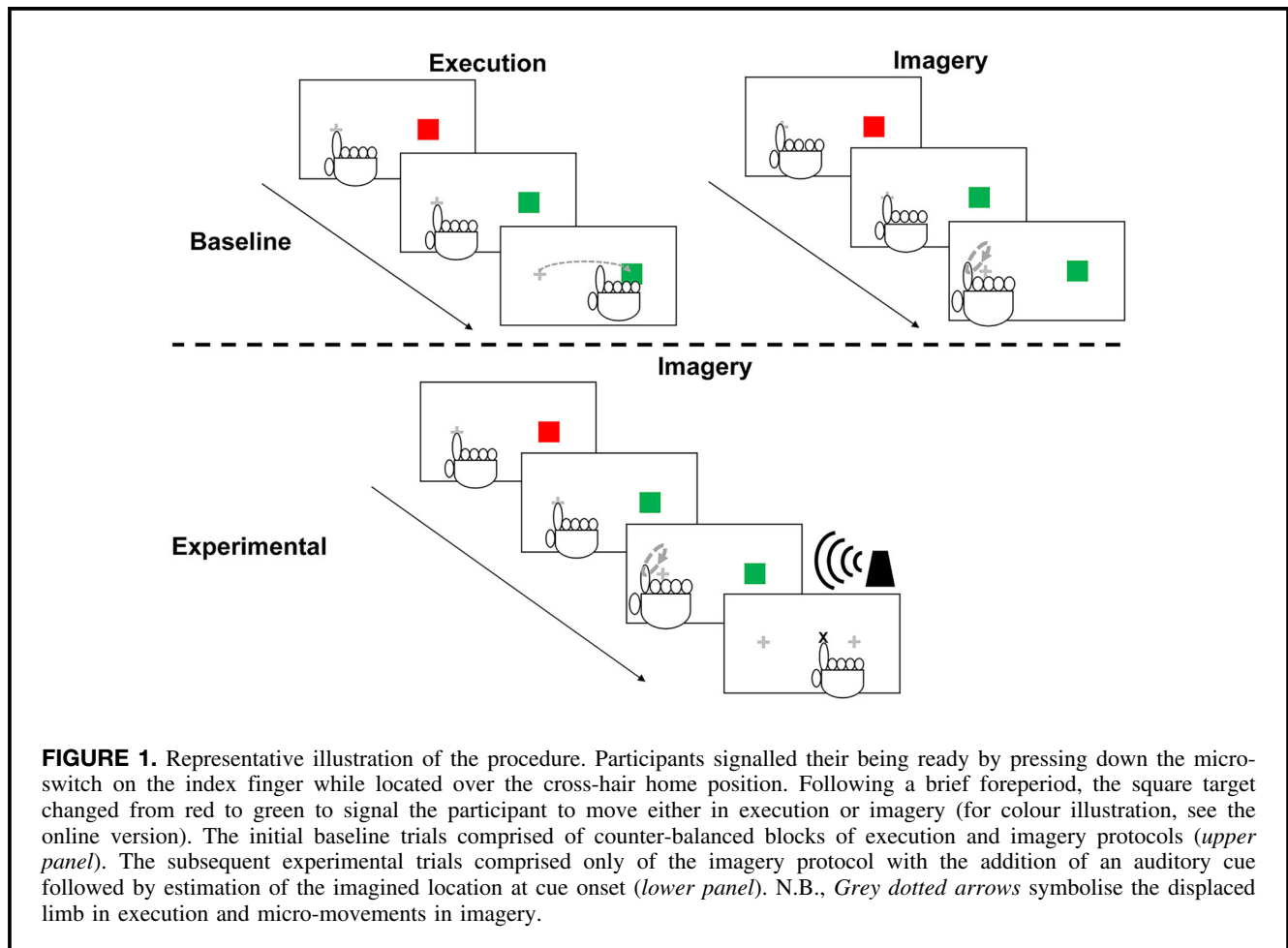
Baseline Trials

In the baseline trials, participants had to complete aiming movements within the execution and imagery protocols (Figure 1; upper panel). To begin a trial, participants would press the micro-switch on the index finger to the screen near the home position as represented by a grey-coloured cross-hair (10-mm length and 1-mm width lines). At the same time, there was also a square target object shown in solid red (15×15 mm) towards the right of the home position at either 12, 24 and 48 cm amplitudes. Following a 2-sec foreperiod, the target would turn solid green to signal the participant to move in their own time.

For the execution protocol, participants would initiate their movement by lifting the limb to release the micro-switch and traverse across to the target where they would then re-contact the surface by pressing down on the microswitch. For the imagery protocol, participants were instructed to imagine themselves see and feel the aiming movement. To indicate their imagined movement, they would first lift the limb up to release the microswitch and hold it until they wanted to terminate the imagined movement where they would make contact with the surface once again by pressing down on the microswitch. In this regard, the execution and imagery protocols featured the same temporal events at the start and end of each trial (i.e., release and press of the microswitch), although only the former involved physically moving to the target. The execution and imagery protocols were each blocked and presented in a counter-balanced order across participants. They each featured 24 trials consisting of 8 trials per ID, which were presented in a fully randomised order.

Experimental Trials

In the experimental trials, the procedure was run in much the same way as within the baseline trials (Figure 1; lower panel). That is, participants attempted only the imagery protocol, which involved using the micro-switch to indicate the start and end of a movement. However, on a select portion of trials (50% of trials), there was an additional auditory cue that appeared either early (25% of movement time) or late (75% of movement time) within the trial. These moments were independently selected for each participant depending on their own mean imagined movement time at baseline for each ID (e.g., baseline movement time $= 1000$ ms; early cue $= 250$ ms, late cue $= 750$ ms). Thereafter, there was an instruction on the monitor that appeared for 1 sec that informed participants to estimate the position of limb from when they first heard the tone. During this time, both the home and target positions from the most recent attempt were highlighted with grey cross-hairs, and participants had up to 3 secs to place the limb in the very position that they imagined it would have been at the moment of the previous auditory cue. The position of the marker on the finger was detected and recorded on the external motion capture system as manually controlled by the experimenter. There were a total of 48 trials comprising of 24 cued trials with 8 trials per ID, which were presented in a fully randomised order.

FIGURE 1. Representative illustration of the procedure. Participants signalled their being ready by pressing down the micro-switch on the index finger while located over the cross-hair home position. Following a brief foreperiod, the square target changed from red to green to signal the participant to move either in execution or imagery (for colour illustration, see the online version). The initial baseline trials comprised of counter-balanced blocks of execution and imagery protocols (*upper panel*). The subsequent experimental trials comprised only of the imagery protocol with the addition of an auditory cue followed by estimation of the imagined location at cue onset (*lower panel*). N.B., *Grey dotted arrows* symbolise the displaced limb in execution and micro-movements in imagery.

Data Handling and Analysis

Firstly, we calculated movement time as the time difference between the start and end of the movement, which was taken from release and press of the micro-switch, respectively. Bearing in the mind the main purpose of baseline and experimental trials, we forwarded movement times for all baseline trials and only the experimental trials with a cue to the statistical analysis, while discarding the experimental trials without a cue. In addition, we also calculated the proportion of the movement time to the auditory cues within each cued trial in order to check whether the cues generally unfolded at the time that was intended.

The post-trial estimated locations involved time-series displacement data, which were smoothed using a 2nd order, zero-phase lag Butterworth filter with a low-pass cut-off frequency of 8 Hz. The movement trace from each individual trial was initially observed to ensure that any samples comprising displacement of the limb when first reaching for the selected final position were subsequently trimmed prior to any calculus. The mean of the remaining samples was then taken as the final position. The estimate itself was calculated as the distance between the start and final positions. Herein, we calculated the within-participant mean and standard deviation in estimated locations, where the tendency and consistency in distinguishing between the auditory cues could be respectively highlighted. In this regard, a clear distinction between these cues would render a shorter within-participant mean estimate for the early compared to late condition, but an equally small within-participant variation for each of the conditions. These data are available *via* the Open Science Framework (https://osf.io/934xp).

Movements within baseline and experimental trials with a cue were analysed using two-way repeated-measures Analysis of Variance (ANOVA) including factors of protocol (execution, imagery) and ID (4, 5, 6). Meanwhile, the mean and variability of the estimated location were analysed using another two-way ANOVA including factors of cue (early, late) and ID (4, 5, 6). In the event of a statistically significant effect involving the factor of ID, then it was reasonable to follow up with a linear trend analysis based on the assumption that there would be an incremental effect of task difficulty on performance (Fitts, 1954; Fitts & Peterson, 1964). Significance was declared at $p < .05$.

RESULTS

Baseline Trials

There was a significant main effect of protocol, $F(1,9)$ = 16.15, p = .003, η_p^2 = .64, and ID, $F(2,18)$ = 33.34, p < .001, η_p^2 = .79. However, these effects were superseded by a significant protocol x ID interaction, $F(2,18)$ = 12.49, p < .001, η_p^2 = .58, where movement times increased more following increases in target amplitude for the imagined (4ID M (±SD) = 892 ± 459 ms, 5ID M (±SD) = 1189 ± 481 ms, 6ID M (±SD) = 1618 ± 762 ms) compared to executed (4ID M (±SD) = 476 ± 127 ms, 5ID M (±SD) = 629 ± 130 ms, 6ID M (±SD) = 713 ± 178 ms) protocol, $F(1,9)$ = 18.52, p = .002, η_p^2 = .67 (linear) (Figure 2A).

Experimental Trials

For imagined movement time, there was no significant main effect of cue, $F(1,9)$ = 3.68, p = .087, η_p^2 = .29. However, there was a significant main effect of ID, $F(2,18)$ = 50.66, p < .001, η_p^2 = .85, indicating increases in time following increases in the target amplitude, $F(1,9)$ = 58.59, p < .001, η_p^2 = .87 (linear) (4ID marginal M (±SD) = 904 ± 327 ms, 5ID marginal M (±SD) = 1199 ± 384 ms, 6ID marginal M (±SD) = 1537 ± 510 ms) (Figure 2B). Meanwhile, there was no significant cue x ID interaction, $F(2,18)$ = 1.39, p = .276, η_p^2 = .13.[1] Therefore, it appears a mental chronometry effect was similarly generated in the experimental trials as it was in the baseline trials.
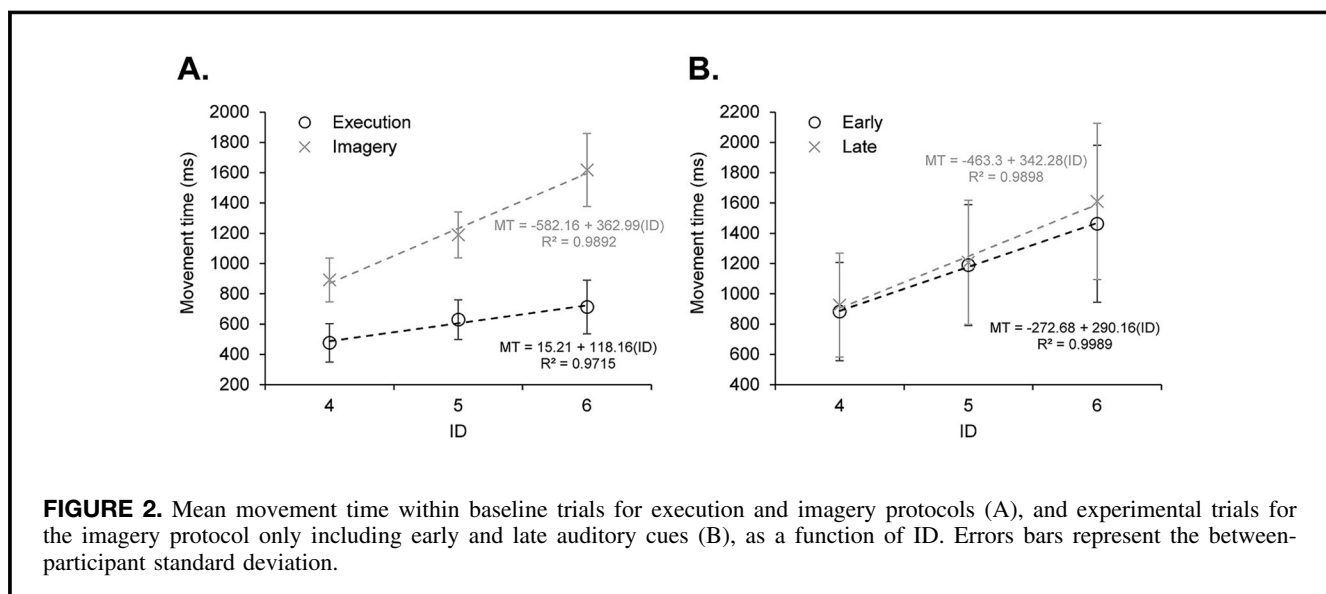
As a manipulation check, the proportion of time to the early and late auditory cues revealed a significant main effect of cue, $F(1,9)$ = 106.74, p < .001, η_p^2 = .92, whe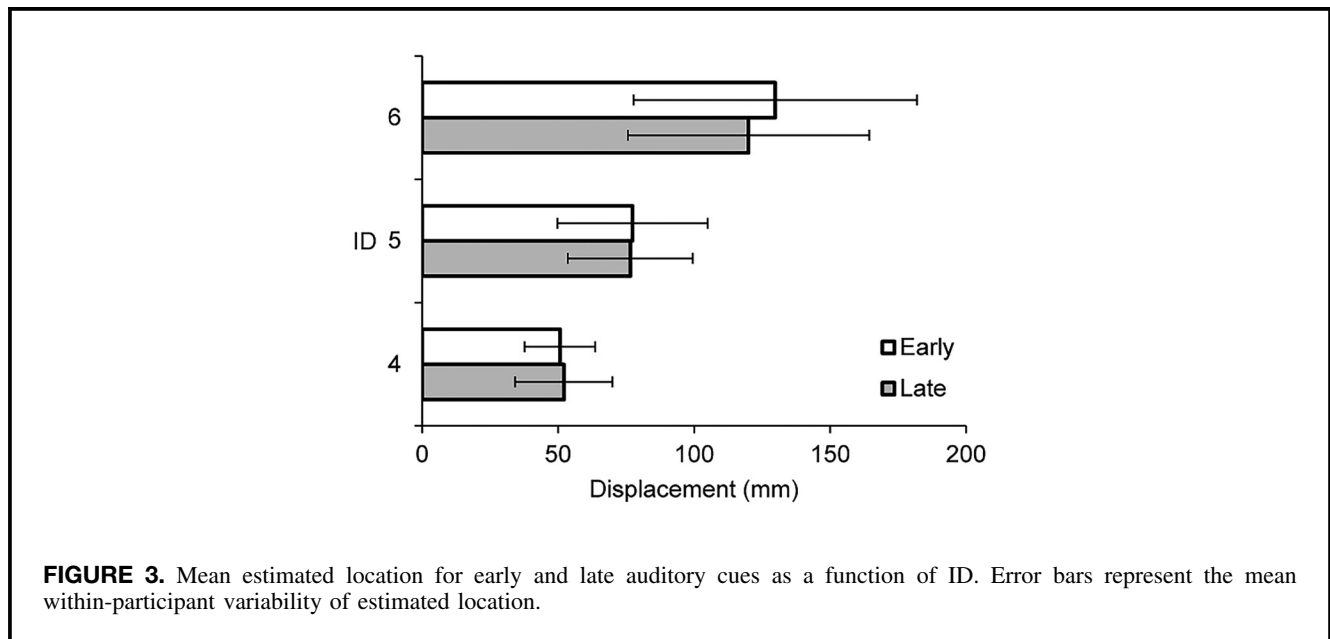re the auditory cue appeared sooner for the early compared to late condition. Moreover, the range of mean times across the IDs for each of the early (M range = 26.17-29.77%) and late (M range = 76.63-80.80%) conditions suggests that the auditory cues were presented at a time near what was intended (25% vs. 75%). Meanwhile, there was no significant main effect of ID, $F(2,18)$ = .77, p = .470, η_p^2 = .08, nor a significant cue x ID interaction, $F(2,18)$ = .03, p = .969, η_p^2 = .003.

Most importantly, for the mean estimated location for each of the cues, there was no significant main effect of cue, $F(1,9)$ = .45, p = .521, η_p^2 = .05, although there was a significant main effect of ID, $F(2,18)$ = 33.49, p < .001, η_p^2 = .79, where estimates were located at a further point in space following increases in target amplitude, $F(1,9)$ = 38.45, p < .001, η_p^2 = .81 (linear) (4ID marginal M (±SD) = 52 ± 20 mm, 5ID marginal M (±SD) = 77 ± 26 mm, 6ID marginal M (±SD) = 125 ± 52 mm) (Figure 3). Meanwhile, there was no significant cue x ID interaction, $F(2,18)$ = 1.02, p = .35, η_p^2 = .10. The within-participant variability (i.e., standard deviation) of estimated location revealed no significant main effect of cue, $F(1,9)$ = .84, p = .384, η_p^2 = .09, although there was a significant main effect of ID, $F(2,18)$ = 11.45, p = .007, η_p^2 = .56, where estimates were more greatly dispersed following increases in target amplitude, $F(1,9)$ = 12.40, p = .006, η_p^2 = .58 (linear) (4ID marginal M (±SD) = 15 ± 5 mm, 5ID marginal M (±SD) = 25 ± 9 mm, 6ID marginal M (±SD) = 48 ± 30 mm). Also, there was no significant cue x ID interaction, $F(2,18)$ = 2.01, p = .163, η_p^2 = .18.

Supplementary Analysis

Despite the clear distinction in the time of early and late cues, there appeared a limited recollection of the spatial locations of imagined movements at these times.

FIGURE 2. Mean movement time within baseline trials for execution and imagery protocols (A), and experimental trials for the imagery protocol only including early and late auditory cues (B), as a function of ID. Errors bars represent the between-participant standard deviation.

FIGURE 3. Mean estimated location for early and late auditory cues as a function of ID. Error bars represent the mean within-participant variability of estimated location.
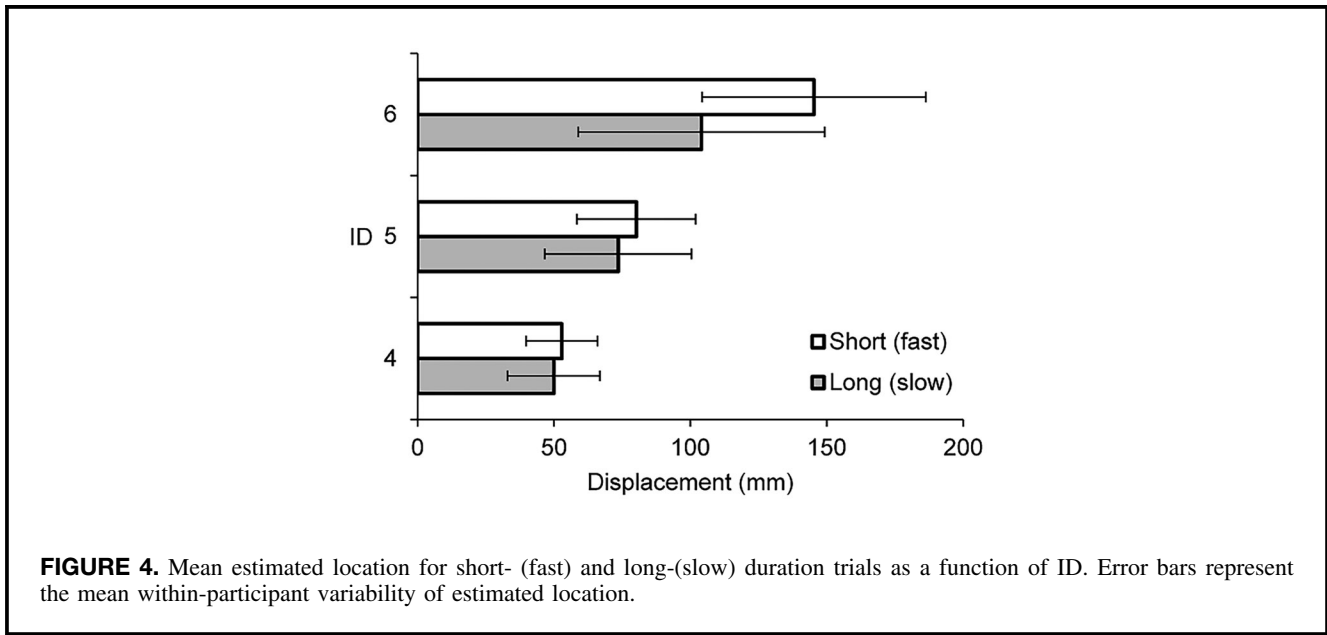
While this finding primarily refutes the simulation of spatial trajectories in motor imagery, it could also be argued that there was a possibility participants failed to accurately register the auditory cues within the trials themselves. However, in order to corroborate and provide an alternative means to examine this issue, we hypothesised that if there was the possibility of simulating the spatial trajectories–and the registration of auditory cues was negligible–then an increase in movement velocity should manifest in a greater distance and variability of post-trial estimates (see Schmidt et al., 1979). Because of the absence of any actual movement to reach the target amplitude, it is not possible to derive velocity from motor imagery per se. Nevertheless, it is reasonable to assume that there is an inverse relation between velocity and movement time (i.e., an increase in velocity manifests in a shorter movement time) within a set ID such that any differences resulting from movement velocity may be equally captured by movement time. With this in mind, we disregarded the factor of auditory cue, and instead categorised trials as either short- and long-duration depending on a median split of the movement times within each target amplitude for each participant. Therein, in a similar vein to our previous main analysis, we conducted a two-way repeated-measures ANOVA with factors of trial (short-, long-duration) and ID (4-6).

Firstly, for imagined movement time, there was a main effect of trial, $F(1,9) = 63.20$, $p < .001$, $\eta_p^2 = .88$, where naturally, times decreased for the short- (marginal M $(\pm SD) = 988 \pm 365$ ms) compared to long-duration (marginal M $(\pm SD) = 1438 \pm 445$ ms) trials. There was a significant main effect of ID, $F(2,18) = 50.71$, $p < .001$, $\eta_p^2 = .85$, indicating increases in time following increases in the target amplitude, $F(1,9) = 58.21$, $p < .001$, $\eta_p^2 = .87$

(linear). Meanwhile, there was no significant trial x ID interaction, $F(2,18) = 3.08$, $p = .071$, $\eta_p^2 = .26$, with a trend towards a marginally smaller increase in time following increases in target amplitude for the short- (4ID M $(\pm SD) = 701 \pm 294$ ms, 5ID M $(\pm SD) = 987 \pm 357$ ms, 6ID M $(\pm SD) = 1278 \pm 478$ ms) compared to long-duration (4ID M $(\pm SD) = 1100 \pm 371$ ms, 5ID M $(\pm SD) = 1415 \pm 436$ ms, 6ID M $(\pm SD) = 1799 \pm 564$ ms) trials.

For mean estimated location within each of the trial categories, there was a significant main effect of trial, $F(1,9) = 5.50$, $p = .044$, $\eta_p^2 = .38$, and ID, $F(2,18) = 33.27$, $p < .001$, $\eta_p^2 = .79$. However, these effects were superseded by a significant trial x ID interaction, $F(2,18) = 6.21$, $p = .032$, $\eta_p^2 = .41$, indicating that the further estimates in space for short- (4ID M $(\pm SD) = 53 \pm 19$ mm, 5ID M $(\pm SD) = 80 \pm 29$ mm, 6ID M $(\pm SD) = 145 \pm 69$ mm) compared to long-duration (4ID M $(\pm SD) = 50 \pm 21$ mm, 5ID M $(\pm SD) = 74 \pm 25$ mm, 6ID M $(\pm SD) = 104 \pm 46$ mm) trials tended to increase following increases in target amplitude $F(1,9) = 5.86$, $p = .039$, $\eta_p^2 = .39$ (linear) (Figure 4). Meanwhile, the within-participant variability of estimated location revealed no significant main effect of trial, $F(1,9) = 3.73$, $p = .085$, $\eta_p^2 = .29$, with a trend towards estimates becoming more dispersed for the long- (marginal M $(\pm SD) = 30 \pm 15$ mm) compared to short-duration (marginal M $(\pm SD) = 25 \pm 11$ mm) trials. However, there was a significant main effect of ID, $F(2,18) = 12.54$, $p = .005$, $\eta_p^2 = .58$, where estimates were more greatly dispersed following increases in target amplitude, $F(1,9) = 14.19$, $p = .004$, $\eta_p^2 = .61$ (linear) (4ID marginal M $(\pm SD) = 15 \pm 5$ mm, 5ID marginal M $(\pm SD) = 24 \pm 3$ mm, 6ID marginal M $(\pm SD) = 43 \pm 8$ mm). Finally, there was no trial x ID interaction, $F(2,18) = .02$, $p = .98$, $\eta_p^2 = .002$.

FIGURE 4. Mean estimated location for short- (fast) and long-(slow) duration trials as a function of ID. Error bars represent the mean within-participant variability of estimated location.

To corroborate the aforementioned findings, we calculated the individual participant gradient/slope coefficients pertaining to the relations between mean or within-participant variability of estimated location and movement time. In line with our previous logic, if motor imagery reflects the spatial trajectory such that participants could closely estimate their previously imagined location, then the movement time (synonymous with movement velocity) should negatively covary with the mean and within-participant variability (as captured by the absolute residual errors; | trial estimate − mean estimate |) of estimated location. In other words, short-duration movements (synonymous with a fast velocity) should coincide with a further mean and more variable estimated location.

A series of single sample t-tests were conducted to compare the gradients/slopes with a theoretical value of zero (synonymous with no relation) on each level of ID. For the relation between mean estimated location and movement time, there was a significant negative relation at 4ID, $t(9) = -3.20$, $p = .011$ ($M = -22.92 \pm 22.67$), but not 5ID, $t(9) = -1.10$, $p = .298$ ($M = -13.55 \pm 38.79$), and 6ID, $t(9) = -3.20$, $p = .095$ ($M = -44.86 \pm 76.14$). For the relation between within-participant variability and movement time, there was a significant positive relation at 4ID, $t(9) = 3.45$, $p = .007$ ($M = 6.78 \pm 6.20$), but no significant relation at 5ID, $t(9) = .62$, $p = .552$ ($M = 4.40 \pm 22.53$), and 6ID, $t(9) = .25$, $p = .806$ ($M = 3.14 \pm 39.26$).

DISCUSSION

While much has been learned about movement imagery using the mental chronometry paradigm, past research has been somewhat limited to the temporal characteristics of movement. The present study examined whether movement imagery captures the spatial characteristics that comprise movement trajectories. Thus, we had participants initially execute and imagine rapid aiming movements with different levels of ID. These imagined movement times were adapted to configure auditory cues that would appear near 25% and 75% of the mean imagined movement time for a separate set of imagined movements.

Firstly, for baseline trials, we successfully replicated the mental chronometry effect, whereby there was an increasing imagined time following an increase in ID. There was a longer movement time within the imagined compared to executed protocol, which became even more apparent with increases in ID. Meanwhile, for the experimental trials, there was a limited effect of cue on post-trial spatial estimation despite there being a distinct separation in time between when the early and late cues had sounded. However, further inspection of the spatial estimates at each level of ID as a function of movement time (synonymous with movement velocity) revealed some evidence for them being located further along, but less widely spread following shorter movement times.

The initial mental chronometry effect successfully corroborates the vast empirical literature that has featured the mental chronometry paradigm (for a review, see Guillot & Collet, 2005). That is, when individuals imagine movements they tend to take longer when the task is made more difficult, which is a feature that is also prominent within executed movements (e.g., Decety & Jeannerod, 1995; Papaxanthis et al., 2002). As a result, this effect has been strongly leveraged as support for the functional equivalence model, whereby an internal representation is correspondingly used for imagery and execution (Jeannerod, 1994, 1999).

Though imagined and executed movement times demonstrated a similar relation with ID, there was a longer movement time for imagined compared to executed movements that became increasingly the case following increases in ID. This finding is not without precedence with other studies having even elaborated on a potential explanation for this difference. Indeed, the recently formulated motor-cognitive model suggests that the more prolonged times for imagined movements manifest from a greater use of executive resources to consciously generate and monitor an image as a way to substitute for the lack of online sensory feedback (Glover & Baran, 2017; Glover et al., 2020; see also, Martel & Glover, 2023). On the other hand, the time-course of imagined movements may become shorter and more similar to the executed movements when an internal representation can be adequately refined following prior sensorimotor experience, and thus limit the need for any online sensory feedback (Yoxon, Pacione et al., 2017; Yoxon, Tremblay et al., 2015).

Although there appeared no effect of the cue on estimated locations, there was some evidence to indicate an effect of movement time or speed. That is, locations appeared farther and less variable following shorter times or faster movements. The former would suggest that imagery appropriately captured the spatial trajectory because faster movements reach further into the distance. However, the latter is at odds with lawful functions of human movement, where there is typically an inverse relation between spatial variability and movement time; that is, more variability following faster movements (Schmidt et al., 1979). The failure in imagery to capture this particular feature has been indicated elsewhere when individuals showed a limited relation between the variability of post-trial estimated endpoint locations and movement times within a temporally-constrained paradigm (Roberts et al., 2020). Thus, any possibility for movement imagery to adequately capture the spatial characteristics can be purely limited to the voluntary or intended sources with next to no possibility of it extending to the random stochastic properties.

At this juncture, we may more closely consider the possible differences in the imagery and execution. Namely, while functional equivalence alludes to their similarity in terms of them using a single or common internal representation, there are fundamental differences in their sensorimotor processes. For example, as briefly mentioned earlier (Glover et al., 2020; Glover & Baran, 2017), only during execution is it possible to incorporate sensory feedback. Specifically, the sensory feedback within movement can be adapted to compare with predictions on the dynamic sensory consequences and state of the sensorimotor system ('forward models'), which then feeds into the subsequent generation or modification of outgoing motor signals ('inverse model') (Miall & Wolpert, 1996;

Wolpert & Ghahramani, 2000). In the absence of this sensory feedback during imagery, it effectively precludes the fore mentioned processes, which may inadvertently compromise the fidelity of the simulation. Meanwhile, any attempt to substitute for this sensory feedback through the recruitment of executive resources to consciously generate and monitor an image, may be too vague or coarse to derive a precise spatial trajectory.

Along these lines, recent evidence has highlighted the importance of combining observation with imagery. For example, it has been shown that motor learning outcomes (Marshall et al., 2020; Romano-Smith, Roberts, Wood, et al., 2018; Romano-Smith, Wood, Wright, et al., 2018; Romano-Smith et al., 2019) and corticospinal excitability (Bruton et al., 2020; Wright et al., 2018) incur an additive effect of combined action-observation and motor imagery (AOMI) compared to each of these forms of simulation alone (for recent reviews, see Eaves et al., 2022; Scott et al., 2021). These benefits have been explained by dual-action simulation of representations manifesting separately from AO and MI that can assimilate or merge together (Bruton et al., 2020; Eaves et al., 2016), and/or the use of online visual information courtesy of AO to act as a referent for guiding the already ignited representation from MI (Meers et al., 2020; Vogt et al., 2013). Such processes may be attributed to a unique set of neural substrates including the occipito-temporal regions for AO, and dorsolateral prefrontal cortex, cerebellum and basal ganglia for MI (Hardwick et al., 2018). Thus, it is possible that the presently investigated capacity to simulate the spatial trajectory during imagery may rely upon additional sensory input such as AO to help facilitate this process.

Despite the present findings and subsequent explanations, we would be remiss to not consider the potential limitations of the present study. Firstly, it is relevant to consider that the current measure surrounding spatial characteristics was gleaned post-trial following the incidence of movement imagery itself. Thus, it is possible that this measure was somewhat insensitive to the spatial trajectory during movement imagery. Indeed, a key assumption of the present study was that individuals had to be consciously aware of their movement in order to subsequently reflect upon it after each of the cued trials. However, previous research from executed aiming movements would suggest this may not be the case as we can often veer or correct our movements without necessarily recalling this sort of information (Binsted et al., 2007; Cressman et al., 2006, 2007; Goodale et al., 1986; Heath et al., 2008; Lawrence et al., 2023; Proteau et al., 2009). Likewise, if imagined movements partly rely on executive resources to generate an image as the movement unfolds (Glover & Baran, 2017), then it is possible that there would be too few available resources in order to adequately retain this sort of information for post-trial

estimation. That said, there was some influence of movement time or speed on the post-trial estimated locations. Indeed, if this measure was entirely insensitive to the prior events of imagined movements, then we would anticipate no such effect of time or speed because the locations would be merely selected at random. Therefore, we suggest that while post-trial estimated locations offer a particularly coarse measure of the spatial trajectory within movement imagery, they can provide at least some indication of the spatial characteristics in terms of highlighting any profound and systematic bias.

From a practical perspective, we also recognise that there are limited other opportunities to capture the spatial trajectory within movement imagery owing to an absence of any physical execution. Indeed, it is precisely this reason that the literature may have seemingly negated this line of research. However, there is the possibility for future research to incorporate a more immediate measure of the spatial characteristics as movement imagery unfolds within real-time. For example, our lab is in the midst of adopting an alternative interference task paradigm, whereby individuals additionally undertake a secondary motor task with a spatial trajectory that is incongruent with the imagined movement (e.g., Piedimonte et al., 2018; Ramsey et al., 2010). Moreover, we intend to examine any carry-over effects, where imagined movements may contaminate the spatial characteristics of subsequent executed movements (e.g., Glover & Dixon, 2013).

In conclusion, we present findings that clearly corroborate the mental chronometry effect, as well as the tendency for imagined movement times to increasingly exceed executed movement times. Any disparity in this regard may be explained by the continued need for, but subsequent lack of, online sensory feedback, which cannot be appropriately compensated for during motor imagery. Meanwhile, we find somewhat meagre evidence for the possibility of imagery appropriately capturing the spatial characteristics of movement. This possibility is almost certainly limited to voluntary or intended sources of spatial characteristics (as indicated by the mean), and not those associated with random stochastic properties (as indicated by spatial variability). Future research may extend upon the current study by more directly comparing executed and imagined movements, and adopting concurrent methods of capturing the spatial characteristics within the trials themselves (e.g., stop and estimate location at the moment of cue, executed movements that are incongruent with imagined movements).

NOTE

1. The requirement to additionally respond to an auditory cue within the experimental trials presents a dual-task scenario that may potentially compromise the imagined movement. Thus, we separately analysed movement times using a two-way repeated-measures ANOVA with factors of trial block (baseline, experimental without cue, experimental with early cue, experimental with late cue) and ID (4, 5, 6). Specifically for the trial block factor that is of primary interest, there was no significant main effect of trial block, $F(3,27) = 1.15$, $p = .346$, $\eta_p^2 = .11$, nor a significant trial block x ID interaction, $F(6,54) = 1.07$, $p = .390$, $\eta_p^2 = .11$.

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