Online corrections can occur within movement imagery: An investigation of the motor-cognitive model

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ABSTRACT

The motor-cognitive model proposes that movement imagery additionally requires conscious monitoring owing to an absence of veridical online sensory feedback. Therefore, it is predicted that there would be a comparatively limited ability for individuals to update or correct movement imagery as they could within execution. To investigate, participants executed and imagined target-directed aiming movements featuring either an unexpected target perturbation (Exp. 1) or removal of visual sensory feedback (Exp. 2). The results of both experiments indicated that the time-course of executed and imagined movements was equally influenced by each of these online visual manipulations. Thus, contrary to some of the tenets of the motor-cognitive model, movement imagery holds the capacity to interpolate online corrections despite the absence of veridical sensory feedback. The further theoretical implications of these findings are discussed.

1. Introduction

Movement imagery—the mental simulation of movement in the absence of overt movement itself—has long been known to enhance the performance and (re-)learning of skills (e.g., Dijkerman, Ietswaart, Johnston, & MacWalter, 2004; Ramsey, Cumming, & Edwards, 2008; Reiser, Büsch, & Munzert, 2011; Romano Smith, Wood, Coyles, Roberts, & Wakefield, 2019; Romano-Smith, Roberts, Wood, Coyles, & Wakefield, 2022; Vogt, 1995; Wakefield, Roberts, & Wood, 2020; Wright & Smith, 2009). One of the foremost accounts of these findings is *functional equivalence*, where the mere imagery of movement is deemed to be functionally equivalent to the execution (and observation) of it (Jeannerod, 1994, 1999). In other words, the internal representation or neural codes used for imagery are also those responsible for execution (see also, Hommel, Müsseler, Aschersleben, & Prinz, 2001).

This view has been strongly evidenced by neurophysiological findings including the increased effector-specific corticospinal excitability following movement imagery (Fadiga et al., 1998; Wright et al., 2018), as well as the similar patterns of activation within the inferior frontal/premotor neural regions following movement imagery and execution (Filimon, Nelson, Hagler, & Sereno, 2007; Hétu et al., 2013; Schubotz & von Cramon, 2004). Perhaps the strongest support to-date within the behavioural literature comes from the mental chronometry paradigm, where imagined movement time is captured by short micro-movements or press/release to index the start and end without any overt movement in between. Here, it is shown that the time for both executed and imagined movements can be near equally related to task difficulty (Decety & Jeannerod, 1995; Gueugneau, Crognier, & Papaxanthis, 2008; Gueugneau, Pozzo, Darlot, & Papaxanthis, 2017; Rozand, Lebon, Papaxanthis, & Lepers, 2015; Roberts, Welsh, & Wakefield, 2019; for a review, see

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Guillot & Collet, 2005)— something otherwise known as *Fitts' Law* (Fitts, 1954; MT[movement time] = a[intercept] + (b[gradient] • ID [index of difficulty]). Specifically, it takes longer to complete executed or imagined movements when a task is made more difficult by having a longer amplitude and smaller width of the intended target, which can be defined by the Index of Difficulty[ID] = $\log_2$((2 • A [amplitude]) / W[width]).

More recently, the *motor-cognitive model* (Glover & Baran, 2017; Glover, Bibby, & Tuomi, 2020; Martel & Glover, 2023) has been proposed as an alternative and more viable explanation for the processes underpinning movement imagery. That is, while movement imagery comprises the same motor representation that is also responsible for execution, it is only during imagery that additional conscious processes involving executive resources may be required. To elucidate, if the initial motor representation is deemed inadequate or unable to reach the intended target, then individuals may compensate for this discrepancy by attempting the conscious monitoring and generation of an image. This process is perhaps most prevalent within high precision tasks, where the initial motor representation holds a low-fidelity with respect to the desired outcome, and there is uncertainty surrounding the motor commands required to achieve it. As a result, it manifests in imagined movement times being prolonged following a delay to the indexing response (e.g., key press). Indeed, the typically longer time spent within imagery compared to execution has been shown to increase even more as a task becomes more difficult or complex (Glover & Baran, 2017; see also, Calmels, Holmes, Lopez, & Naman, 2006). Along these lines, this difference begins to decrease when individuals are more physically exposed or trained at the task to-be-imagined (Wong, Manson, Tremblay, & Welsh, 2013; Yoxon, Pacione, Song, & Welsh, 2017; Yoxon, Tremblay, & Welsh, 2015). Presumably, such training interventions provide ample opportunity to refine the representation so it obtains a high-fidelity with respect to the desired outcome, and thus limits the need for the conscious monitoring and generation of an image.

Building upon these original findings, more recent evidence in support of this model has principally manipulated the underlying cognitive component to movement imagery; namely, the enhanced use of executive resources. In this regard, it has been shown that a cognitively demanding mental arithmetic or word generation task can more greatly delay the time it takes within movement imagery compared to execution (Glover et al., 2020). Further still, the use of repetitive transcranial magnetic stimulation (rTMS) to create a temporary virtual lesion near a neural region most closely associated with executive function; that is, the dorsolateral prefrontal cortex, has been shown to also delay the time within movement imagery compared to execution (Martel & Glover, 2023).

An underlying assumption of the motor-cognitive model is that tasks or scenarios requiring more online corrections to the movement through the incorporation of sensory feedback may prove somewhat problematic for movement imagery (Glover & Baran, 2017). To elucidate, a representation that holds a low-fidelity with the desired outcome, and thus proves inadequate to achieve the intended target, would then have to be compensated by consciously monitoring and generating the image when they would otherwise use sensory feedback to amend any error and guide the movement during execution. This logic is somewhat adapted from the notion of the two-component model of stereotypical target-directed movements, where the initial and more ballistic portion of the movement is primarily a manifestation of a motor representation that is accessed within offline planning prior to the movement itself, while the latter and slower portion enables more time for processing sensory feedback subject to additional online corrections (Woodworth, 1899; Keele & Posner, 1968; Zelaznik, Hawkins, & Kisselburgh, 1983; Elliott, Helsen, & Chua, 2001; Khan et al., 2003; Proteau, Roujoula, & Messier, 2009; for a recent review, see Elliott et al., 2017).

That said, it could be argued that this view somewhat conflicts with the alternative and perhaps more contemporary framework comprising an internal forward model for feedforward control (Grush, 2004; Rieger, Boe, Ingram, Bart, & Dahm, 2023). Here, an efference copy of the initial motor command may continue to be generated before the inhibition of motor signals reaching the periphery. This copy is adapted to form an internal forward model that can closely predict the sensory feedback from the ongoing movement. As a result, it is possible for the errors of imagined movements to be estimated even in the absence of veridical sensory feedback (Ingram, Hurst, Solomon, Stratas, & Boe, 2022; cf. Roberts, Wood, & Wakefield, 2020). Therefore, the predicted sensory feedback from imagined movements could to some extent substitute for the actual sensory feedback that is typically used for online corrections (see Krigolson, Van Gyn, Tremblay, & Heath, 2006).

Classic manipulations designed to more directly examine online corrections have typically featured a perturbation to the sensorimotor environment whilst within the movement. For example, the intended target may suddenly shift to an alternative position so that individuals must update their ongoing movement if they are to successfully reach the target (e.g., Grierson & Elliott, 2008; Heath, Hodges, Chua, & Elliott, 1998; Mendoza, Elliott, Meegan, Lyons, & Welsh, 2006; Oostwoud Wijdenes, Brenner, & Smeets, 2013; Zhang, Brenner, Duysens, Verschueren, & Smeets, 2018). In a similar vein, the visual information that helps to initially programme the movement may suddenly be removed at movement onset so that individuals can no longer use visual feedback to amend any error and guide the movement toward the target (e.g., Elliott et al., 2014; Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006; Khan et al., 2003; Khan, Elliott, Coull, Chua, & Lyons, 2002; Zelaznik et al., 1983).

To this end, we aimed to assess the capacity of movement imagery for simulating online corrections in response to externally induced perturbations, and in so doing, examine the explanatory power of the motor-cognitive model. Specifically, we adapted the fore mentioned manipulations, where individuals would imagine and execute movements following an unexpected target perturbation (Exp. 1), and the removal of visual sensory feedback (Exp. 2). If the motor-cognitive model offers a robust explanation, including the limited ability to simulate online corrections owing to an absence of sensory feedback during imagery, then we would anticipate there to be less of an influence of the target perturbation and visual sensory feedback for imagery compared to execution. However, if motor imagery is better accustomed at simulating online corrections without necessarily relying on the conscious monitoring and generation of an image, then there should be a relatively equal response (as indicated by changes in reaction and/or movement time) to the online target perturbation and availability of visual sensory feedback within imagery and execution.

2. Experiment 1

2.1. Introduction

The motor-cognitive model of movement imagery states that a motor representation of a high-fidelity need not use an excess amount of executive resources in order to consciously monitor and generate an image. However, a low-fidelity representation would require further support from such conscious processes because there is less reliance upon the initial motor representation, and no available online sensory feedback as would normally be the case for executed movements (Glover & Baran, 2017). To-date, this logic has been primarily evidenced by the exponentially greater rise in movement time following an increase in difficulty for imagined compared to executed movements (Glover et al., 2020; Glover & Baran, 2017; Yoxon et al., 2015; Yoxon et al., 2017).

As a further examination of this model, it was reasoned that any failure of movement imagery to compensate for a low-fidelity representation, because of the use of conscious processes to effectively substitute for veridical online sensory feedback, would render a limited ability of these conscious processes to adjust to an unexpected perturbation involving a pre-planned target location. Therefore, the aim of this experiment was to examine the capacity for imagery to simulate online corrections following a target perturbation. Participants aimed to one of three possible targets that were located at different set amplitudes (short/medium/long), which acted as an experimental control (unperturbed trials). Meanwhile, in another block of trials, participants would aim to one of these three possible targets (medium), which occasionally shifted position at movement onset so they would appear either closer to (short) or further away (long) from the participants' aiming limb (perturbed trials) (Grierson & Elliott, 2008; Heath et al., 1998).

In order to corroborate the intended manipulation following our online perturbation, and in line with the two-component model of manual aiming (Elliott et al., 2001; Keele & Posner, 1968; Woodworth, 1899), we firstly hypothesized a more prolonged movement time during execution following a target perturbation, whereby the trajectory could be appropriately corrected and successfully reach the target location. However, according to the motor-cognitive model, we hypothesized that while movement imagery may more generally prolong reaction and movement times compared to execution, it would not necessarily encounter a change in movement time as a function of target perturbation owing to a limited correction to the trajectory.in the absence of veridical sensory feedback.

2.2. Methods

2.2.1. Participants

A total of 16 participants (9 = female, 7 = male, 12 = right-hand dominant, 4 = left-hand dominant (self-reported), age $M = 23.05$, $SD = 5.52$) volunteered for Experiment 1 having signed an informed consent form. The present sample was chosen based on an estimated sample size of 16 courtesy of an apriori power analysis using G*Power (v. 3.1.9.3; Faul, Erdfelder, Lang, & Buchner, 2007), which included the following parameters: $\eta_p^2 = 0.13$ (large) (from an interaction between perturbation and protocol), $\alpha = 0.05$, $1-\beta = 0.80$, correlation among repeated measures = 0.5, non-sphericity correction $\varepsilon = 1$. The estimated effect size was based on large
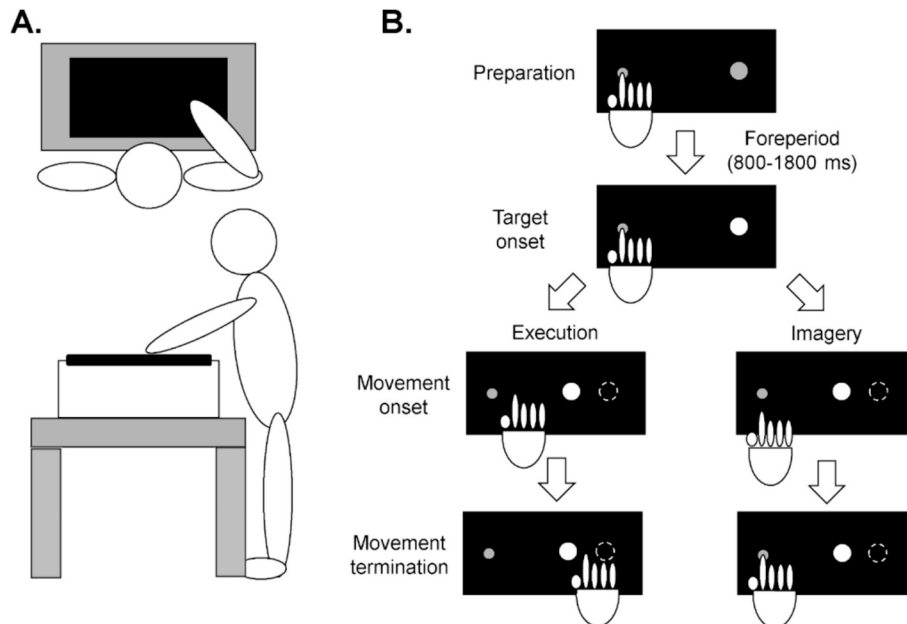

Fig. 1. Representative illustration of the experimental set-up taken from the transverse (*upper panel*) and sagittal (*lower panel*) (A). In addition, a representative illustration of the experimental events for execution and imagery protocols. The present example demonstrates a perturbation trial involving the target switching from a medium (*unfilled circle within dotted outline*) to short (*solid circle*) amplitude following movement onset (B).

movement time effect sizes within a combination of previous studies including a target perturbation protocol (Heath et al., 1998) and imagined movements within low- and high-precision tasks (Glover et al., 2020; Glover & Baran, 2017).

2.2.2. Apparatus

Stimuli were presented on an LCD monitor (dimensions = 47.5 × 27.0 cm, spatial resolution = 1920 × 1080 pixels, temporal resolution = 75 Hz), which was covered by a 2-mm-thick transparent acrylic sheet and placed on top of a polystyrene box that was mounted on a table at near waist-height (see Fig. 1A). This stimuli consisted of a black background with a 5-mm grey circle positioned on the left side to indicate the home position, and 15-mm circle positioned on the right side representing the target. The stimuli were controlled using a custom-written MATLAB programme (v. 2018b; MathWorks, Natick, MA) running Psychtoolbox (v. 3.0.11; Pelli, 1997).

Participants wore a lycra glove with a NO button microswitch (Saia-Burgess Electronics, Murten, Switzerland) securely attached to the underside of the tip of the index finger on the right hand facing down toward the aiming surface and connected to a computer via serial port. A retro-reflective marker was also placed on the tip of the same finger facing upward (parallel with the microswitch). The movement trajectories of the reflective marker were captured using an optoelectric motion capture system (Vicon Vantage, Vicon Motion Systems Ltd., Oxford, UK) (temporal resolution = 200 Hz sampling frequency (5 ms per frame), spatial resolution = 16-megapixel). The system recorded data for 3 s per trial, which was manually controlled by the experimenter using Vicon Nexus software (v. 2.5).

2.2.3. Task and procedure

Participants were tasked with the execution and imagery of a single aiming movement. This task involved participants standing over the aiming surface looking directly down onto the display with their mid-sagittal axis near aligned with the home position. A trial would commence by pressing down over the home position with the microswitch on the tip of the index finger. Following an 800–1800-ms variable delay, the target would change from grey to white to signal the participants to move. For execution, participants would physically aim as quickly and accurately as possible. Specifically, they would start by releasing the microswitch on the tip of the finger at the home position and move from left-to-right along the transverse plane before finally pressing the microswitch back down over the target position. For imagery, participants were instructed to vividly imagine themselves see and feel the aiming movement as quickly and accurately as possible. In a similar vein to execution, participants initially released the microswitch at the home position. However, they remained over the home position until finally pressing the microswitch back down. The moments of the initial release and final press of the microswitch were taken as the start and end of the imagined movement, respectively. This indexing response was reminiscent of a series of other studies featuring the mental chronometry paradigm (e.g., Gueugneau et al., 2008, 2017; Roberts et al., 2019; Rozand et al., 2015; Yoxon et al., 2015; Yoxon et al., 2017), while it also ensured some degree of overlap between the imagined and executed tasks such that a high-fidelity image could be formed (e.g., see PETTLEP; Wakefield, Smith, Moran, & Holmes, 2013; Wright & Smith, 2009) without necessarily manifesting in any overt motor output.

There were three possible target amplitudes including short (amplitude = 175 mm; ID = 4.54 bits), medium (amplitude = 200 mm; ID = 4.74 bits), and long (amplitude = 225 mm; ID = 4.91 bits). For the control trials, these target amplitudes were set without changing them within individual trials, and they were presented an equal number of times. For the perturbation trials, the medium target was always presented at the start of every trial, and remained so for most of the trials (67%), but occasionally shifted (25 mm) to either a short or long target 50 ms following the initial release of the microswitch (33%) (Grierson & Elliott, 2008; Roberts & Grierson, 2020, 2021) (see Fig. 1B).

In keeping with the recommended number of trials for studies primarily involving performance outcome measures (e.g., reaction time, movement time) (Blinch, Kim, & Chua, 2018; see also, De Grosbois, Crainic, & Tremblay, 2018), there were 10 trials for each of the target amplitudes that were presented randomly within the control trials (total = 30 trials), while there were 40 trials for the medium target (unperturbed) and 10 trials for each of the short and long (perturbed) targets that were presented randomly within the perturbation trials (total = 60 trials). The order of the control and perturbation trials was counter-balanced across participants within each of the execution and imagery protocols. These execution and imagery protocols were also counter-balanced across participants. Prior to data collection, there 3 trials per target for familiarisation/practice (unperturbed) (total = 9 trials).

2.2.4. Data management and analysis

The moments of the start and end of each movement were indicated by the initial release and terminal press of the NO button microswitch, respectively. Three-dimensional Cartesian coordinates from the location of the reflective marker were smoothed using a Butterworth filter of the order 2 with a low-pass cut-off frequency of 8 Hz (dual-pass). Instantaneous velocity, acceleration and jerk from the primary axis of the movement within only the execution trials (x-axis) were calculated by using the two-point central difference method to take the first, second and third derivatives of displacement, respectively. The moment of terminal endpoint for each trial was determined by parsing backward from recordings to the moment velocity reached >30 mm/s or < −30 mm/s for at least 40 ms (8 frames). Target positions were calibrated by simply taking additional recordings of the index finger located over a series of crosshairs that were displayed on the screen and overlaid the centre position for each of the targets featured within the study.

Position data from the external motion capture system was used only to corroborate the adjustments that were needed for the target perturbation within actual movement from the execution trials only. In this regard, we calculated the participant mean radial error, where the radial distance between the terminal endpoint and target centre was taken. Further still, we calculated the proportion of time to peak velocity by taking the time to peak velocity relative to the total movement time expressed as a percentage, where it was assumed that a longer time after peak velocity would indicate more time within online corrections (Hansen et al., 2006; Khan et al.,

2002; Roberts & Bennett, 2022). Along these lines, we also captured the proportion of trials involving two-component movements consisting of a primary and secondary submovement phase, whereby any error accumulated within the former would typically be corrected within the latter (Elliott et al., 2001, 2017; Woodworth, 1899). In order to further highlight the nature these submovement corrections, we also captured the proportion of trials involving different types of submovement (Hsieh, Pacheco, Liu, & Newell, 2022; Roberts, Burkitt, & Elliott, 2024). To elucidate, we parsed forward frame-by-frame from peak negative acceleration to the first moment of either a positive-to-negative zero-line crossing in velocity (type 1; synonymous with a reversal), negative-to-positive zero-line crossing in acceleration (type 2; synonymous with a second acceleration), or positive-to-negative zero-line crossing in jerk (type 3; synonymous with discontinuities/braking).

Meanwhile, the temporal events captured by the microswitch provided the key dependent measures for both execution and imagery protocols including participant mean reaction time (i.e., time difference between stimulus target onset and the initial release of the microswitch) and movement time (i.e., time difference between the initial release and terminal press of the microswitch).

Any trials that featured a reaction time < 100 ms (i.e., false start) or movement time > 2 SDs away from the grand mean were removed prior to any further calculation and analysis (2.47% of trials). Radial error, proportion of time to peak velocity and proportion of two-component movement trials for execution trials only were statistically analysed using a two-way fully repeated-measures Analysis of Variance (ANOVA) including factors of perturbation (perturbed, unperturbed) and target (short, medium, long). Alternatively, the proportion of trials with different submovement types was analysed using a three-way fully repeated-measures ANOVA including factors of type (type 1–3, none), perturbation (perturbed, unperturbed), and target (short, medium, long). Meanwhile, reaction time and movement time were each analysed using a three-way fully repeated-measures ANOVA including factors of perturbation (perturbed, unperturbed), protocol (execution, imagery) and target (short, medium, long).

Sphericity was evaluated using Mauchly's test and any subsequent violations were corrected using the Huynh-Feldt corrected-value when Epsilon was ≥0.75, although the Greenhouse-Geisser corrected-value was used if otherwise (original uncorrected degrees-of-freedom are reported). Statistically significant effects featuring more than two means were decomposed using Tukey's Honestly Significant Difference (HSD) post hoc procedure. Significance was declared with alpha set to $p < .05$, and effect sizes were indicated using partial eta squared (η_p^2) (including 95% CI).

2.3. Results and discussion

For execution trials only, radial error revealed no significant main, nor interaction effects within execution trials ($ps > 0.05$) (see Table 1). Thus, it appears individuals were still able to successfully reach the target following the onset of a perturbation.

In order to more definitively indicate a correction to the perturbation, the proportion of time to peak velocity revealed a significant main effect of perturbation, $F(1,15) = 7.12, p = .018, \eta_p^2 = 0.32$, 95% CI [0.01 0.58], and target, $F(2,30) = 9.98, p = .00, \eta_p^2 = 0.40$, 95% CI [0.11 0.57], although these were superseded by a significant perturbation x target interaction, $F(2,30) = 6.70, p = .004, \eta_p^2 = 0.31$, 95% CI [0.04 0.50]. Post hoc analysis indicated a significantly shorter proportion of time to peak velocity for the short and long compared to medium (unperturbed) target amplitudes within the perturbation trials ($ps < 0.05$). In a none-too-dissimilar vein, the proportion of two-component movement trials indicated a significant main effect of perturbation, $F(1,15) = 10.24, p = .006, \eta_p^2 = 0.41$, 95% CI [0.04 0.63], and target, $F(2,30) = 11.24, p = .00, \eta_p^2 = 0.43$, 95% CI [0.13 0.59], although these were superseded by a significant perturbation x target interaction, $F(2,30) = 4.86, p = .015, \eta_p^2 = 0.25$, 95% CI [0.01 0.44]. Post hoc analysis indicated a significantly greater proportion of two-component movement trials for the short and long compared to medium target amplitudes within the perturbation trials, although there was only a significantly greater proportion for the long compared to medium target amplitude within the control trials ($ps < 0.05$).

Further inspection of the two-component movements; that is, the proportion of trials with different types of submovement, revealed a significant main effect of type, $F(1,15) = 22.61, p = .00, \eta_p^2 = 0.60$, 95% CI [0.21 0.76], and only a main effect of target that

Table 1
Radial error (mm), proportion of time to peak velocity (%), proportion of trials with a two-component movement (%) and proportion of trials with different submovement types (%) (type 1–3, none) (±SE) for execution trials as a function of perturbation (control, perturbation) and target (short, medium, long) (N.B., medium target for perturbation trials remained unperturbed).

	Control			Perturbation		
	Short	Medium	Long	Short	Medium	Long
Radial error (mm)	7.97 (0.60)	7.91 (0.60)	8.40 (0.55)	9.57 (1.54)	8.92 (1.03)	8.25 (0.71)
Time to peak velocity (%)	37.43 (1.11)	38.58 (1.30)	37.64 (1.36)	33.34 (1.84)	38.47 (1.45)	33.96 (1.84)
Two-component (%)	61.47 (6.80)	53.91 (6.65)	62.85 (3.94)	87.48 (4.00)	64.39 (5.09)	80.40 (4.76)
Type 1 (%) (reversal)	35.14 (7.52)	33.36 (5.89)	35.14 (4.32)	80.89 (4.03)	47.18 (4.83)	27.95 (5.79)
Type 2 (%) (second acceleration)	8.69 (2.66)	3.55 (1.66)	8.19 (2.28)	1.32 (0.09)	5.63 (1.65)	13.54 (3.64)
Type 3 (%) (discontinuities)	17.64 (4.92)	17.01 (5.47)	19.51 (3.74)	5.28 (2.23)	11.58 (2.62)	38.91 (5.76)
None (%) (single-component)	38.53 (6.80)	46.09 (6.65)	37.15 (3.94)	12.52 (4.00)	35.61 (5.09)	19.60 (4.76)

approached conventional levels of significance, $F(2,30) = 3.18$, $p = .056$, $\eta_p^2 = 0.18$, 95% CI [0.00 0.37]. Meanwhile, there was a significant type x perturbation interaction, $F(3,45) = 8.26$, $p = .002$, $\eta_p^2 = 0.36$, 95% CI [0.11 0.50], and type x target interaction, $F(6,90) = 14.32$, $p = .00$, $\eta_p^2 = 0.49$, 95% CI [0.31 0.57], although these were superseded by a significant type x perturbation x target interaction, $F(6,90) = 12.69$, $p = .00$, $\eta_p^2 = 0.46$, 95% CI [0.27 0.55]. Post hoc analysis indicated a significantly greater proportion of trials with a type 1 submovement (reversal) for the short compared to medium target amplitude, which was greater still compared to the long target amplitude within the perturbation trials ($ps < 0.05$). While there were no significant differences for proportion of trials with a type 2 submovement (second acceleration) ($ps > 0.05$), there was significantly smaller proportion of trials with a type 3 submovement (discontinuities/braking) for the short and medium compared to long target amplitudes within the perturbation trials ($ps < 0.05$). Meanwhile, for the remaining proportion of trials without a secondary submovement (single-component movement), there was a significantly smaller proportion of them for the short and long compared to medium target amplitudes within the perturbation trials ($ps < 0.05$). Taken together, it appears individuals corrected for a short target perturbation by later reversing the limb following a brief overshoot toward the medium target location, while correcting for a long target perturbation by "homing-in" after an initial undershoot over the medium target location.

Reaction time revealed no significant main, nor interaction effects ($ps > 0.05$), although the main effect of protocol approached conventional levels of significance, $F(1,15) = 3.43$, $p = .084$, $\eta_p^2 = 0.19$, 95% CI [0.00 0.47], indicating a longer time for imagery compared to execution (see Fig. 2A).

Movement time revealed no significant main effect of perturbation, $F(1,15) = 2.78$, $p = .116$, $\eta_p^2 = 0.16$, 95% CI [0.00 0.44], although there was a significant main effect of protocol, $F(1,15) = 5.66$, $p = .031$, $\eta_p^2 = 0.27$, 95% CI [0.00 0.54], and target, $F(2,30) = 6.16$, $p = .006$, $\eta_p^2 = 0.29$, 95% CI [0.03 0.48]. These effects were superseded by a significant perturbation x target interaction, $F(2,30) = 8.04$, $p = .002$, $\eta_p^2 = 0.35$, 95% CI [0.07 0.53]. Post hoc analysis indicated a significantly shorter time for the short compared to medium and long target amplitudes within control trials, although there was a significantly longer time for the short and long compared to medium (unperturbed) target amplitudes within the perturbation trials ($ps < 0.05$) (see Fig. 2B). There were no further significant interactions ($ps > 0.05$), including no significant perturbation x protocol x target interaction, $F(2,30) = 0.002$, $p = .998$, $\eta_p^2 = 0.00$, 95% CI [0.00 0.003].

To corroborate the fore mentioned effects within each of the imagery and execution protocols, we separately ran a two-way repeated measures ANOVA including factors of perturbation and target for imagery and execution. For imagery, there was no significant main effect of perturbation, $F(1,15) = 0.02$, $p = .89$, $\eta_p^2 = 0.00$, 95% CI [0.00 0.05], although there was a significant main effect of target, $F(2,30) = 5.90$, $p = .007$, $\eta_p^2 = 0.28$, 95% CI [0.03 0.47]. Further still, there was a significant perturbation x target interaction, $F(2,30) = 3.36$, $p = .048$, $\eta_p^2 = 0.18$, 95% CI [0.00 0.38]. Post hoc analysis indicated a significantly shorter time for the short compared to medium and long target amplitudes within control trials ($ps < 0.05$). Meanwhile, there was no longer a significant difference between short and medium target amplitudes ($p > .05$), while there was a significantly longer time for the long compared to medium target amplitude within perturbation trials ($p < .05$). For execution, there was a significant main effect of perturbation, $F(1,15) = 11.63$, $p = .004$, $\eta_p^2 = 0.44$, 95% CI [0.06 0.65], but no significant main effect of target, $F(2,30) = 2.30$, $p = .118$, $\eta_p^2 = 0.13$, 95% CI [0.00 0.33]. These effects were superseded by yet another significant perturbation x target interaction, $F(2,30) = 4.98$, $p = .014$, $\eta_p^2 = 0.25$, 95% CI [0.01 0.44]. Post hoc analysis indicated no significant difference between the short and medium target amplitudes ($p > .05$), although there was a significantly shorter time for the short compared to long target amplitude within the control trials ($p < .05$). However, there was a significantly longer time for the short and long compared to medium (unperturbed) target amplitudes within the perturbation trials ($ps < 0.05$).

In sum, participants appeared to prolong their reaction and movement times for imagery compared to execution. Meanwhile, the movement time was extended whenever there was a perturbation (short/long) compared to no perturbation (medium) for both imagery and execution protocols. These findings indicate that movement imagery generally takes longer within offline planning of the
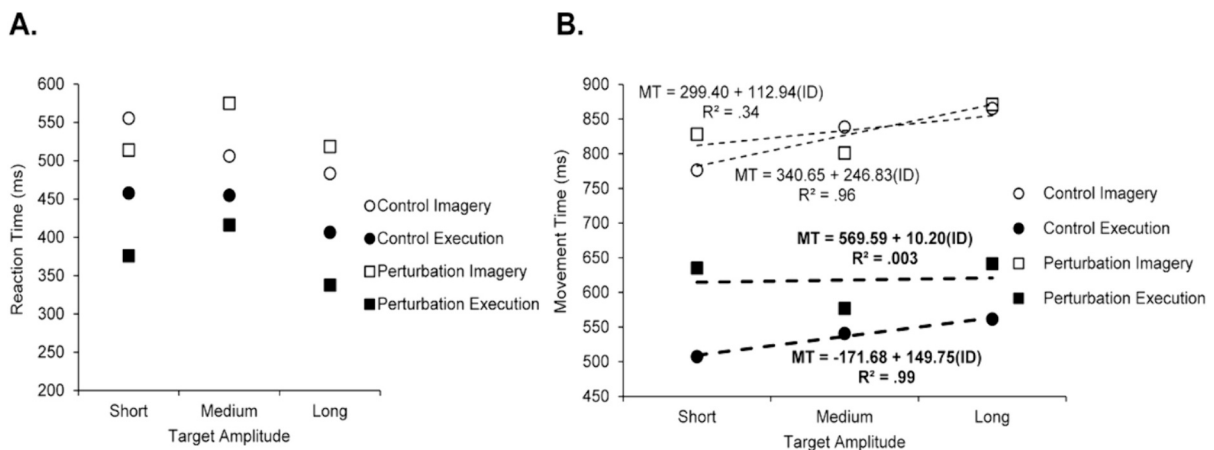

Fig. 2. Mean reaction time (A) and movement time (B) as a function of perturbation and protocol (see legend), and target amplitude (horizontal axis). N.B., Linear trends and equations for execution are emboldened.

imagined movement itself (Calmels et al., 2006; Glover & Baran, 2017; Yoxon et al., 2015; Yoxon et al., 2017). However, most importantly, there appeared to be a relatively equal response to the perturbation for movement imagery and execution, which indicates how imagery was just as capable as execution in capturing the necessary online corrections. That is, participants were somehow able to interpolate the online corrections to the pre-planned simulated trajectory. As a result, these findings may conflict with the tenets of the motor-cognitive model (Glover & Baran, 2017), which indicates a problem for movement imagery in being able to appropriately simulate online corrections due to an absence of veridical sensory feedback (for more detail, see the *General Discussion*).

However, it is important to recognise that the current direction of effects pertaining to each of the perturbations (i.e., short and long amplitudes) were somewhat incompatible with the trend identified within the literature (Grierson & Elliott, 2008; Heath et al., 1998). That is, previous studies have featured a trend that is perhaps more befitting of Fitts' linear relation (Fitts, 1954), where movement times are less for the short compared to medium (unperturbed) amplitude, which is shorter still compared to the long amplitude. These discrepancies may be attributed to the subtle differences within each of the studies. For example, the same target perturbation has been previously issued within a two-dimensional virtual aiming set-up (Heath et al., 1998), whilst the present study featured a three-dimensional real-life arrangement. Meanwhile, the previously adopted range of amplitudes comprising both perturbed and unperturbed target trials have been comparatively large (23–27 cm; Grierson & Elliott, 2008) as opposed to the presently small-to-mid range that was adopted here. (17.5–22.5 cm). Nevertheless, because online corrections can take a longer time to implement; particularly toward the end of the trajectory (Elliott, Carson, Goodman, & Chua, 1991; Elliott, Chua, Pollock, & Lyons, 1995; Hansen et al., 2006; Khan et al., 2002; Roberts & Bennett, 2022; Woodworth, 1899), it is still taken that the present pattern of results alludes to corrections being made as a result of the target perturbation.

In comprehending the potential capacity for movement imagery to simulate online corrections, it is perhaps worthwhile considering the role of eye movements. Indeed, within a stereotypical visually-regulated target-directed aiming task, the eyes typically precede the limb in fixing onto the target location so that it enters into the high-acuity central visual field (Helsen, Starkes, Elliott, & Buekers, 1998; Land, 2009). Previous research has shown that a similar pattern of oculomotor behaviour is naturally adopted within movement imagery (Causer, McCormick, & Holmes, 2013; Heremans, Helsen, & Feys, 2008; McCormick, Causer, & Holmes, 2013). Further still, it is this oculomotor behaviour that may precisely facilitate movement imagery (Gueugneau et al., 2008; Heremans et al., 2011; Pathak, Patel, Karlinsky, Taravati, & Welsh, 2023; Wakefield et al., 2020). Thus, the simulated online corrections that are evident within the present study may have partially manifested as a by-product of oculomotor behaviour, where the eyes could freely move and likely shift whenever there was target perturbation.

3. Experiment 2

3.1. Introduction

While the motor-cognitive model contends that movement imagery often compensates for a low-fidelity representation by using executive resources to consciously monitor and generate an image, which may preclude our ability to simulate online corrections, the evidence from Experiment 1 would thus far suggest otherwise. That is, it appears that while the time of imagined movements continues to exceed executed movements (Glover & Baran, 2017), the apparent corrections that were simulated within imagined movements were rather similar to the actual corrections made within executed movements. That said, these corrections may have been facilitated by the additional oculomotor extra-retinal information manifesting from a shift in the target location (see Causer et al., 2013; Heremans et al., 2008; McCormick et al., 2013; Wakefield et al., 2020).

We now seek to primarily corroborate the fore mentioned findings, while adopting a functionally distinct approach that accounts for any potential confounds in Experiment 1 (on the merits of such approaches, see Fiedler, 2011). To do so, we adapted another classic manipulation of online sensory feedback. Specifically, participants executed and imagined aiming movements to one of three possible target locations either with full visual feedback or following the removal of visual feedback at movement onset. Importantly, this visual feedback manipulation was ordered in a blocked fashion so participants could respectively anticipate and plan a movement that would accommodate for the presence or absence of visual sensory feedback (Hansen et al., 2006; Khan et al., 2002). In this regard, it is typically shown that without visual feedback during executed movements, individuals tend to take more time prior to the movement and less time within it because they can more heavily invest in offline planning without necessarily relying on visual sensory feedback for online corrections, respectively.

Thus, we hypothesized that participants would exhibit a shorter reaction time and longer movement time for vision compared to no vision conditions during executed movements (Hansen et al., 2006; Khan et al., 2002). Meanwhile, according to the motor-cognitive model, we hypothesized that while participants may generally take longer in reaction and movement times for imagery compared to execution, they would not necessarily distinguish between vision and no vision conditions for imagined movements because the former already encounters no veridical visual sensory feedback. However, in line with the findings from Experiment 1, where participants demonstrated at least some capacity to simulate online corrections, we may alternatively reveal a pattern of results for imagined movements that is somewhat similar to executed movements.

3.2. Methods

3.2.1. Participants

A total of 17 participants (female = 6, male = 11, right-hand dominant = 15, age M = 21.94 years, SD = 4.37) volunteered for Experiment 2 having signed an informed consent form. The present sample was chosen based on an estimated sample size of 16

courtesy of an apriori power analysis using G*Power (v. 3.1.9.3; Faul et al., 2007), which included the following parameters: $\eta_p^2 = 0.13$ (large) (from an interaction between vision and protocol), $\alpha = 0.05$, $1-\beta = 0.80$, correlation among repeated measures = 0.5, non-sphericity correction $\varepsilon = 1$. The estimated effect size was based on large movement time effect sizes within a combination of previous studies including a visual sensory feedback manipulation (Hsieh et al., 2022) and imagined movements within low- and high-precision tasks (Glover et al., 2020; Glover & Baran, 2017). The study was designed and conducted in accordance with the Declaration of Helsinki (1964), and approved by the local institutional research ethics committee.

3.2.2. Apparatus

Stimuli were presented on a CRT monitor (size = 17 in., spatial resolution = 1280 × 1024 pixels, temporal resolution = 85 Hz), which was placed on a table facing participants with the screen-centre at near eye level courtesy of a height-adjustable chair (see Fig. 3A). This stimuli consisted of a white background with a grey 15-mm square positioned on the left side to indicate the home position, and a grey circle positioned on the right side representing the target. There were three possible combinations of target amplitude and width that were designed to assume different levels of ID including 4 (amplitude = 120 mm, width = 15 mm), 5 (amplitude = 180 mm, width = 11.25 mm), and 6 (amplitude = 240 mm, width = 7.5 mm) bits. The stimuli were controlled using a custom-written MATLAB programme (2018b; MathWorks, Natick, MA) running Psychtoolbox (v. 3.0.11; Pelli, 1997). All testing was conducted within a dark laboratory setting.

Participants used their right hand to hold a stylus pen, which was captured on a graphics digitizing tablet (GTCO Calcomp Drawing Board VI, GTCO CalComp, Scottsdale, AZ) (temporal resolution = 125 Hz (8 ms per frame), spatial resolution = 1000 lines per inch). The tablet was placed on a separate table underneath the display and covered with a height-adjustable shelving unit to occlude vision of the limb. The movement trajectories of the stylus pen were translated to a black cross-hair cursor (8-mm length x 1-mm thickness) on the monitor (1:1 mapping).

3.2.3. Task and procedure

In a similar vein to Experiment 1, participants were tasked with the execution and imagery of a single aiming movement. A trial would commence by pressing down with the nib of the stylus while the cursor was positioned over the home position. Following a 800–2300-ms variable delay, a target would appear to signal the participant to a move. For execution, the participants would physically aim as quickly and accurately as possible with the nib released, but still in contact with the tablet. For imagery, participants would vividly imagine the aiming movement as quickly and accurately as possible with the nib released and pressed back down to indicate start and end of the imagined movement, respectively.

For both execution and imagery protocols, the visual feedback of the cursor and target were either continually presented or
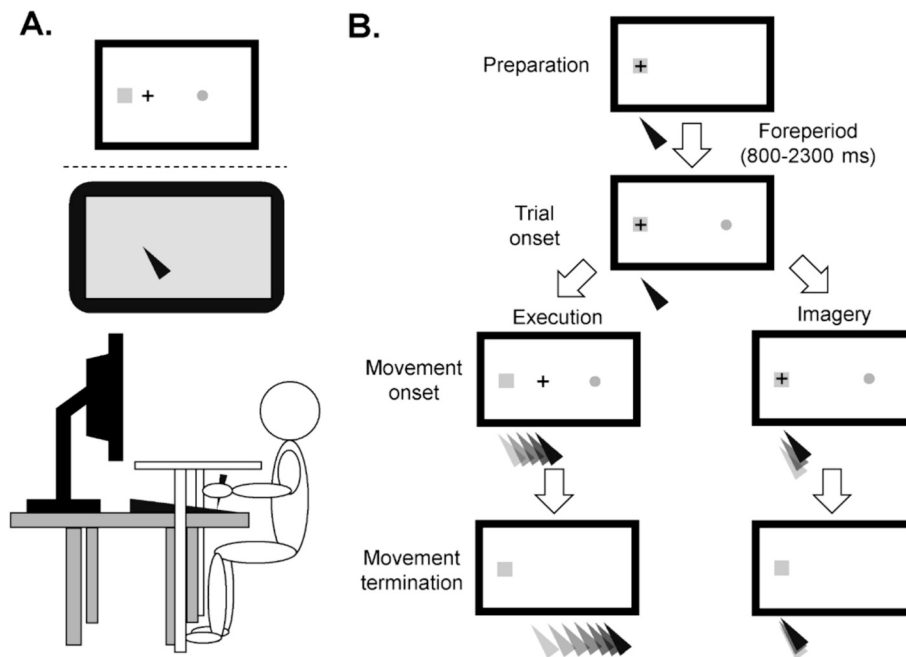

Fig. 3. Representative illustration of the experimental set-up including the stimulus display with the home (*grey square*), cursor (*black cross-hair*) and target (*grey circle*) objects (*upper panel*), and movement of the stylus on the graphics digitizing tablet that was beneath the monitor (*lower panel*) (A). In addition, a representative illustration of the experimental events for execution and imagery protocols, including superimposed movement of the stylus coincident with the stimulus. The present example demonstrates a trial with visual sensory feedback following movement onset, but no terminal feedback (B).

disappeared following movement onset. The simultaneous removal of both the cursor and target was based on previous evidence of them each independently influencing endpoint accuracy and precision (e.g., cursor/limb: Carlton, 1981; Rossetti, Stelmach, Desmurget, Prablanc, & Jeannerod, 1994; Ghez, Gordon, & Ghilardi, 1995; target: Elliott & Madalena, 1987; Coello & Magne, 2000). Meanwhile, for the imagery protocol, participants were instructed to imagine themselves see and feel the aiming movement when under vision, but only to feel the movement when under no vision. Terminal visual feedback was removed in the same way for all trials by disappearing the stimulus once the nib was pressed back down.

Importantly, the vision and no vision conditions were presented in a blocked fashion so that participants could adequately prepare for the upcoming sensory feedback condition (see Hansen et al., 2006; Khan et al., 2002; Zelaznik et al., 1983). The order of the blocks was pseudorandomized following a Latin-Square design (Bradley, 1958). There were 12 trials per ID that were presented randomly within each of the blocks (total = 36 trials). Prior to data collection, there was one block of trials completed under the execution protocol with vision for familiarisation/practice.

3.2.4. Data management and analysis

For imagery trials, the reaction time was taken as the time difference between stimulus target onset and the initial release of the nib, while movement time was taken as the difference between the initial release and subsequent press of the nib.

For execution trials, the reaction time was taken as the time difference between stimulus target onset and the moment the cursor (as translated from the limb) reached outside the home position. Meanwhile, the movement trajectories were processed by first smoothing the two-dimensional Cartesian coordinates from the tablet using the same filter parameters as Experiment 1. Instantaneous velocity, acceleration and jerk from the primary axis of the movement (x-axis) were each calculated by using the two-point central difference method to take the first, second and third derivatives of displacement, respectively. A graphical user interface within MATLAB was used to plot and manually pick two points within the velocity profiles to indicate the near start and end of the movement for each trial. Movement time was calculated as the time difference between the moments when velocity reached >30 mm/s having parsed forward from the first pick, and parsed backward from the second pick. In addition, these velocity thresholds had to be upheld for at least 40 ms (5 frames).

Any trials that featured a reaction time < 100 ms (i.e., false start) were removed prior to any further calculation and analysis (0.41% of trials). To corroborate the use of online visual sensory feedback within actual movement from the execution trials only, we calculated the participant mean radial error, proportion of time to peak velocity, and proportion of two-component movement trials, which were each statistically analysed using a two-way fully repeated-measures Analysis of Variance (ANOVA) including factors of vision (vision, no-vision) and ID (4, 5, 6). In addition, we calculated the proportion of trials with different submovement types, which was analysed using a three-way fully repeated-measures ANOVA including factors of type (type 1–3, none), vision (vision, no-vision) and ID (4, 5, 6). However, key dependent measures pertaining to both execution and imagery protocols included participant mean reaction time and movement time, which were analysed using a three-way fully repeated-measures ANOVA including factors of vision (vision vs no-vision), protocol (execution, imagery) and ID (4, 5, 6). The remaining statistical parameters including Sphericity, post hoc, alpha, and effect size followed the same conventions as Experiment 1.

3.3. Results and discussion

For the execution trials only, radial error revealed a significant main effect of vision, $F(1,16) = 42.47$, $p < .001$, $\eta_p^2 = 0.73$, 95% CI [0.40 0.83], and difficulty, $F(2,32) = 4.64$, $p = .017$, $\eta_p^2 = 0.23$, 95% CI [0.01 0.42]. Moreover, there was a significant vision x difficulty interaction, $F(2,32) = 7.38$, $p = .002$, $\eta_p^2 = 0.32$, 95% CI [0.05 0.50], whereby the significantly less error for vision compared to no vision appeared to become even more prevalent with increasing levels of difficulty ($ps < 0.05$) (see Table 2). Thus, it appears individuals were able to take advantage of the visual sensory feedback in order to successfully reach the intended target.

In order to more definitively indicate visually-regulated online corrections, the proportion of time to peak velocity revealed a

Table 2

Mean radial error (mm), proportion of time to peak velocity (%), proportion of trials with a two-component movement (%) and proportion of trials with different submovement types (%) (type 1–3, none) (±SE) for execution trials as a function of vision (vision, no vision) and difficulty (4, 5, 6 bits).

	Vision			No vision		
	4 bits	5 bits	6 bits	4 bits	5 bits	6 bits
Radial error (mm)	5.64 (0.83)	6.70 (1.76)	4.45 (0.47)	29.92 (4.49)	37.58 (5.67)	40.68 (5.25)
Time to peak velocity (%)	35.39 (1.58)	34.70 (0.97)	32.63 (0.81)	43.65 (1.46)	44.84 (1.20)	45.04 (1.19)
Two-component (%)	50.00 (3.54)	66.47 (3.08)	81.76 (3.12)	25.29 (7.28)	30.59 (6.44)	36.21 (6.47)
Type 1 (%) (reversal)	17.65 (4.16)	21.76 (5.83)	15.59 (5.08)	1.76 (1.28)	1.76 (0.95)	0.06 (0.06)
Type 2 (%) (second acceleration)	8.82 (2.08)	12.94 (3.06)	22.35 (4.25)	1.76 (0.95)	4.12 (2.58)	4.77 (2.99)
Type 3 (%) (discontinuities)	23.53 (2.56)	31.76 (4.39)	44.12 (5.76)	21.76 (6.20)	24.71 (5.01)	30.85 (5.21)
None (%) (single-component)	50.00 (3.54)	33.53 (3.08)	18.24 (3.12)	74.71 (7.28)	69.41 (6.44)	63.79 (6.47)

significant main effect of vision, $F(1,16) = 82.29$, $p < .001$, $\eta_p^2 = 0.84$, 95% CI [0.60 0.90], but no significant main effect of difficulty, $F(2,32) = 0.58$, $p = .57$, $\eta_p^2 = 0.04$, 95% CI [0.00 0.18]. However, there was a significant vision x difficulty interaction, $F(2,32) = 3.42$, $p = .045$, $\eta_p^2 = 0.18$, 95% CI [0.00 0.37], whereby the significantly shorter proportion of time to peak velocity for vision compared to no vision ($ps > 0.05$) appeared to become even more prevalent with increasing levels of difficulty. In a similar vein, the proportion of two-component movement trials indicated a significant main effect of vision, $F(1,16) = 38.31$, $p = .00$, $\eta_p^2 = 0.71$, 95% CI [0.37 0.82], and difficulty, $F(2,32) = 35.61$, $p = .00$, $\eta_p^2 = 0.69$, 95% CI [0.46 0.78]. However, these effects were superseded by a significant vision x difficulty interaction, $F(2,32) = 4.49$, $p = .019$, $\eta_p^2 = 0.22$, 95% CI [0.00 0.41], whereby the significantly greater proportion of two-component movement trials for vision compared to no vision ($ps < 0.05$) appeared to become even more prevalent with increasing levels of difficulty.

Further inspection of the two-component movements; that is, the proportion of trials with different types of submovement, revealed a significant main effect of type, $F(3,48) = 38.56$, $p = .00$, $\eta_p^2 = 0.71$, 95% CI [0.53 0.78]. Meanwhile, there was a significant type x vision interaction, $F(3,48) = 20.85$ $p = .00$, $\eta_p^2 = 0.57$, 95% CI [0.34 0.67], and type x difficulty interaction, $F(6,96) = 11.82$, $p = .00$, $\eta_p^2 = 0.43$, 95% CI [0.24 0.51], although these were superseded by a type x vision x difficulty interaction, $F(6,96) = 2.60$, $p = .022$, $\eta_p^2 = 0.14$, 95% CI [0.00 0.22]. Post hoc analysis indicated a significantly greater proportion of trials with a type 1 submovement (reversal) for vision compared to no vision at an ID of 4, 5 and 6 ($ps < 0.05$), while there was a significantly greater proportion with type 2 (second acceleration) and 3 (discontinuities/braking) submovements for vision compared to no vision only at an ID of 6 ($ps < 0.05$). Inversely, there was a significantly smaller proportion of trials with no secondary submovement (single-component movement) for vision compared to no vision at an ID of 4, 5 and 6 ($ps < 0.05$). Taken together, these findings corroborate the intended visual feedback manipulation as individuals tended to use online visual feedback to correct any error by taking longer nearer the end of the movement following peak velocity; a process that was exacerbated following an increase in difficulty, and subsequently movement error.

Reaction time revealed a significant main effect of vision, $F(1,16) = 13.49$, $p = .002$, $\eta_p^2 = 0.46$, 95% CI [0.09 0.66], indicating a shorter time to initiate movement for vision compared to no vision. Meanwhile, there was a significant main effect of protocol, $F(1,16) = 24.14$, $p < .001$, $\eta_p^2 = 0.60$, 95% CI [0.22 0.76], and difficulty, $F(2,32) = 9.52$, $p = .001$, $\eta_p^2 = 0.37$, 95% CI [0.10 0.55]. However, these effects were superseded by a significant protocol x difficulty interaction, $F(2,32) = 8.46$, $p = .001$, $\eta_p^2 = 0.35$, 95% CI [0.07 0.52], whereby the significantly longer time to initiate movement within imagery compared to execution ($ps > 0.05$) tended to increase with each level of difficulty (see Fig. 4A). There were no further significant interactions ($ps > 0.05$), including no significant vision x protocol x difficulty interaction, $F(2,32) = 0.20$, $p = .778$, $\eta_p^2 = 0.01$, 95% CI [0.00 0.12]. A subsequent two-way repeated-measures ANOVA including factors of vision and difficulty was run separately on imagery and execution. For imagery, there was a significant main effect of vision, $F(1,16) = 6.77$, $p = .019$, $\eta_p^2 = 0.30$, 95% CI [0.01 0.55], and difficulty, $F(2,32) = 11.73$, $p < .001$, $\eta_p^2 = 0.42$, 95% CI [0.14 0.59], although there was no significant vision x difficulty interaction, $F(2,32) = 0.75$, $p = .48$, $\eta_p^2 = 0.05$, 95% CI [0.00 0.20]. For execution, there was a significant main effect of vision, $F(1,16) = 15.70$, $p = .001$, $\eta_p^2 = 0.50$, 95% CI [0.12 0.69], although no significant main effect of difficulty, $F(2,32) = 0.52$, $p = .60$, $\eta_p^2 = 0.03$, 95% CI [0.00 0.17], nor a significant vision x difficulty interaction, $F(2,32) = 0.43$, $p = .65$, $\eta_p^2 = 0.03$, 95% CI [0.00 0.16].

Movement time revealed no significant main effect of vision, $F(1,16) = 0.56$, $p = .47$, $\eta_p^2 = 0.03$, 95% CI [0.00 0.28], and protocol, $F(1,16) = 3.22$, $p = .092$, $\eta_p^2 = 0.17$, 95% CI [0.00 0.45], although there was a significant main effect of difficulty, $F(2,32) = 33.24$, $p < .001$, $\eta_p^2 = 0.68$, 95% CI [0.44 0.77], indicating a longer time for the ID of 4 compared to 5 and 6 ($ps < 0.05$). Meanwhile, the protocol x difficulty interaction approached conventional levels of significance, $F(2,32) = 3.93$, $p = .057$, $\eta_p^2 = 0.20$, 95% CI [0.00 0.39], whereby the significantly longer time to complete the movement within imagery compared to execution ($ps < 0.05$) tended to increase with each level of difficulty (see Fig. 4B). There were no further significant interactions ($ps > 0.05$), including no significant vision x protocol x difficulty interaction, $F(2,32) = 0.80$, $p = .46$, $\eta_p^2 = 0.05$, 95% CI [0.00 0.20]. A subsequent two-way repeated-measures ANOVA for imagery revealed no significant main effect of vision, $F(1,16) = 1.34$, $p = .26$, $\eta_p^2 = 0.08$, 95% CI [0.00 0.35], but a
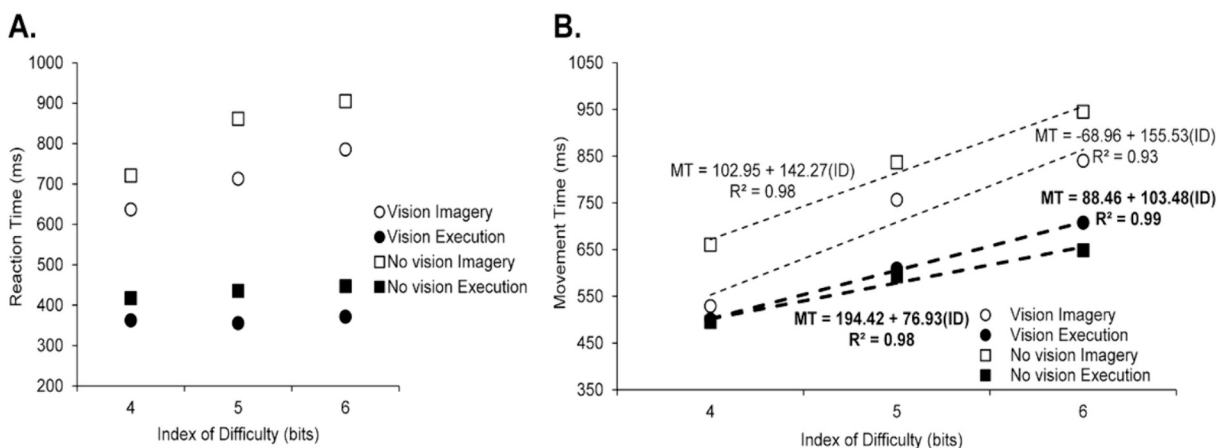

Fig. 4. Mean reaction time (A) and movement time (B) as a function of vision and protocol (see legend), and ID (horizontal axis). N.B., Linear trends and equations for execution are emboldened.

significant main effect of difficulty, $F(2,32) = 17.75$, $p < .001$, $\eta_p^2 = 0.53$, 95% CI [0.24 0.66], while there was no significant vision x difficulty interaction, $F(2,32) = 0.64$, $p = .49$, $\eta_p^2 = 0.04$, 95% CI [0.00 0.18]. In a similar vein, a two-way repeated-measures ANOVA for execution revealed no significant main effect of vision, $F(1,16) = 0.64$, $p = .44$, $\eta_p^2 = 0.04$, 95% CI [0.00 0.29], but there was a significant main effect of difficulty, $F(2,32) = 94.06$, $p < .001$, $\eta_p^2 = 0.86$, 95% CI [0.73 0.90], while there was no significant vision x difficulty interaction, $F(2,32) = 2.73$, $p = .080$, $\eta_p^2 = 0.15$, 95% CI [0.00 0.34].

In sum, participants once more prolonged their reaction and movement times for imagery compared to execution. In line with previous findings (e.g., Calmels et al., 2006; Yoxon et al., 2015; Yoxon et al., 2017), and at least some of the tenets of the motor-cognitive model (Glover & Baran, 2017), these differences were progressively increased as the level of difficulty also increased. However, perhaps more telling with regards the current issue on simulating online corrections was the finding that any differences between vision and no vision conditions in reaction and movement times did not differ as a function of protocol. Thus, it appears movement imagery is not entirely different to execution when it comes to visually-regulated online corrections, and at the very least, prepares a simulation for the use of visual sensory feedback.

Specifically, participants generally exhibited a shorter reaction time under vision compared to no vision, which is a hallmark of comparatively less time spent within offline planning. Presumably, this pattern of results manifests from the knowledge that the presence of visual sensory feedback renders less importance of offline planning with a view to perhaps implementing visually-regulated online corrections later on within the movement (Hansen et al., 2006; Khan et al., 2002). However, typically coincident with this finding would be a longer movement time under vision compared to no vision, which did not unfold in this case within the present study. This null finding is not without precedence (e.g., Elliott & Hansen, 2010), while it is also worth noting that many of the previous studies that have identified differences in movement time as a function of visual sensory feedback have been somewhat marginal (e.g., <60 ms; Hansen et al., 2006; Khan et al., 2002). Thus, we can speculate on the current failure to not quite replicate differences in movement time in that it may be the result of a unique confluence of offline planning and online correction processes. To elucidate, in focusing on the execution protocol only, we can observe that the shorter(longer) proportion of time to(after) peak velocity for vision compared to no vision not only highlights how vision entailed a longer time for visually-regulated online corrections, but also how no vision exhibited a longer time within the initial portions of the trajectory. Because of the negligible differences in movement time, these differences in proportional time may also translate into corresponding changes in absolute time. Therefore, in situations where there was no visual sensory feedback, participants may have taken longer during the initial trajectory by generating less force and limb velocity in order to limit the variability with the understanding that they would not be able to undertake visually-regulated online corrections later on within the movement (e.g., Khan et al., 2002; see also, Allsop, Lawrence, Gray, & Khan, 2017; Roberts, Wilson, Skultety, & Lyons, 2018).

4. General discussion

Movement imagery has been suggested to be functionally equivalent to execution in that it uses many of the same internal processes (Jeannerod, 1994, 1999). Extending upon this concept, the more recent motor-cognitive model (Glover & Baran, 2017) states that movement imagery initially comprises a motor representation that is also responsible for execution followed later on by the conscious monitoring and generation of an image. The latter is perhaps the most integral and novel feature of this model as it indicates the use of executive resources to substitute for the veridical online sensory feedback, which remains elusive during imagery as opposed to execution. This prediction has been supported mostly by findings taken from the mental chronometry paradigm, wherein individuals indicate the start and end of their imagined movements by using a simple indexing response (e.g., key press). Specifically, movement times are known to become exponentially longer for movement imagery compared to execution when the related task is either made more difficult/complex (Glover & Baran, 2017), coincides with a separate cognitively demanding task (Glover et al., 2020) and follows on from a temporary virtual lesion courtesy of rTMS over the dorsolateral prefrontal cortex (Martel & Glover, 2023). With this in mind, a key tenet of the motor-cognitive model surrounds the limited ability of imagery to undertake online corrections owing to an absence of veridical online sensory feedback. Thus, the present study aimed to assess the capacity of movement imagery to simulate online corrections in response to manipulations of online visual sensory feedback including an unexpected shift in the target location (Exp. 1) and the availability of visual feedback within movement (Exp. 2).

Broadly speaking, there was an extended reaction and movement time for imagery compared to execution within both experiments. Additionally, within Experiment 2, this difference tended to increase even more following increased levels of difficulty. These findings may appear consistent with the motor-cognitive model as participants appeared to take longer for offline planning and online corrections as would be assumed following the use of executive resources to consciously monitor and generate an image. However, the online corrections that manifested following each of the manipulations of online visual sensory feedback generally revealed a similar, or none-too-dissimilar, response in movement imagery and execution. This pattern of results would alternatively conflict with the tenets of the motor-cognitive model as participants were able to effectively interpolate online corrections by simulating the use of visual sensory feedback to at least some extent. This is not to say that there is no underlying difference in the executive resources used by imagery and execution, only that imagery does not suffer too greatly from the loss of the veridical sensory feedback when it comes to online corrections, and thus it is more similar to execution than perhaps first thought.

At this juncture, we may try to reconcile the motor-cognitive model with respect to the findings of the present study. Firstly, the motor-cognitive model predicts that while movement imagery features conscious processes to help compensate for the missing veridical online sensory feedback, then execution and the related use of actual online sensory feedback should operate under relatively limited conscious control. This logic is adapted from evidence that actual online corrections within execution may be effort-free (Reichenbach, Franklin, Zatka-Haas, & Diedrichsen, 2014) and go undetected by the individual generating them (Cressman,

Franks, Enns, & Chua, 2007; Goodale, Pelisson, & Prablanc, 1986; Proteau et al., 2009; see also, Lawrence, Khan, & Hardy, 2013). That said, it is important to recognise that not all online corrections exclusively operate in this fashion. For example, recent evidence by Lawrence, Owen, Gottwald, and Khan (2023) indicates how online corrections following a cursor jump (representing the moving limb) were improved or declined following an increase or decrease in the availability of effort/attentional resources, respectively (see also, Cressman, Franks, Enns, & Chua, 2006; Khan et al., 2006). Consequently, it is possible that the online corrections present within movement imagery and execution largely operate on the same level of consciousness.

Secondly, the motor-cognitive model predicts that movement imagery is unable to truly embark on online corrections in the absence of veridical online sensory feedback, although execution may take full advantage of the online sensory feedback with a view to overturning any error that is accumulated across the trajectory. This logic is a direct reflection of the classic closed-loop model, where individuals may simply use sensory feedback within the movement to compare with a target or some form of referent subject to modifying the movement (e.g., Woodworth, 1899). However, this form of online correction pertains only to more unanticipated and delayed corrections that are informed merely by feedback-based processes. These sorts of corrections manifest toward the end of the movement such as following peak limb deceleration and within a secondary submovement that is typically characterised by discontinuities in limb acceleration (Elliott et al., 1995, 2014; Hsieh et al., 2022; Khan, Franks, & Goodman, 1998). Alternatively, it is important to recognise the possibility of more anticipated and rapid corrections that manifest from early feedforward-based processes within offline planning. Specifically, it is proposed that an efference copy can be adapted to form an internal forward sensory model that generates predicted sensory feedback, which when compared with the actual sensory feedback permits the possibility of a correction (Desmurget & Grafton, 2000; Elliott et al., 2017; Wolpert & Ghahramani, 2000; Wolpert, Miall, & Kawato, 1998). It is precisely this process that explains the advent of online corrections shortly after movement onset and as early as the primary submovement following a perturbation to the velocity and/or direction of the moving limb (Blouin, Teasdale, Bard, & Fleury, 1993; Brière & Proteau, 2017; Cressman et al., 2006, 2007; Grierson & Elliott, 2008, 2009; Proteau et al., 2009; Roberts & Grierson, 2020). Along these lines, the use of online visual sensory feedback within movement is often contingent upon planning for its use in advance of the movement itself or following previous experience with this same source of sensory feedback (Burkitt, Staite, Yeung, Elliott, & Lyons, 2015; Cheng, Luis, & Tremblay, 2008; Cheng, Manson, Kennedy, & Tremblay, 2013; Hansen et al., 2006; Khan et al., 1998; 2002; Khan & Franks, 2003; Whitwell, Lambert, & Goodale, 2008; Whitwell & Goodale, 2009). In this regard, because of the influence of offline planning to online corrections, it may at least partially explain how it is that corrections manifest within movement imagery as they do within execution. In other words, the offline planning that underpins movement imagery may effectively drive the interpolation of online corrections irrespective of the absence of veridical sensory feedback (for further discussion, see later within the *General Discussion*).

At this juncture, we may question how it is precisely that movement imagery is able to somehow adapt offline planning for simulating online corrections. One possibility may be drawn from the bioinformational theory of emotional imagery (Lang, 1979; Lang, Kozak, Miller, Levin, & McLean Jr, 1980; see also, Wilson, Smith, Burden, & Holmes, 2010), whereby imagery can naturally stimulate certain physiological responses (e.g., heart rate, muscle contractions, etc) that may be additionally used to update unfolding imagery content. Thus, despite the absence of overt movement, it is possible that any miniscule efferent outflow or "leakage" during movement imagery may provide sufficient information for simulating online corrections.

However, even in the complete absence of this information and related online sensory feedback, the emulation theory of representation (Grush, 2004) also states that imagery can emulate sensory feedback by combining the initial pre-planned response and internal forward sensory model. This emulated sensory feedback can effectively substitute for the actual sensory feedback by having it compared with the predicted sensory feedback. In a none-too-dissimilar vein, the more recent proposal of imagined errors using an internal forward model (Rieger et al., 2023) would have it that while movement imagery is unable to make comparisons between the desired (i.e., intended effect) and actual state, as well as the predicted and actual sensory feedback, it is still possible to make a comparison between internal predictions and the desired state. As a result, imagined movements may subsequently detect and correct a purely imagined error (e.g., Ingram et al., 2022).

In conclusion, there are some findings within the present study that are in agreement with the direction of effects proposed by the motor-cognitive model, including prolonged reaction and movement times for movement imagery compared to execution. These findings can be respectively taken as evidence for a more reinforced contribution of offline planning and alternative use of executive resources during movement imagery. However, this model is limited in terms of how it is that online corrections may alternatively unfold within movement imagery compared to execution. That is, there was clear evidence of online corrections unfolding relatively equally for imagery and execution. We suspect the capacity to simulate online corrections may be explained by facilitative efferent "leakage" and/or simulated sensory feedback courtesy of an internal forward sensory model. These findings offer unique theoretical and applied implications including how performers (e.g., novices) and situations (e.g., difficult/complex) that are more heavily reliant upon online control processes may be appropriately captured through mere movement imagery in the absence of veridical sensory feedback. Furthermore, it provides impetus for future research to more strongly consider the offline planning and online corrections underpinning imagery and execution.

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During the preparation of this work the authors did not use an AI assistive service or technology.

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