Full Length Article

The action-specific effect of execution on imagination of reciprocal aiming movements

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ABSTRACT

Past research has shown that the movement times of imagined aiming movements were more similar to actual movement times after the individual has experienced executing the movements. The purpose of the present study was to determine if experience with a set of movements altered the imagination of movements that were not experienced. Participants imagined a series of reciprocal aiming movements in different movement difficulty contexts (created by altering target width and movement amplitude) before and after actually executing a series of aiming movements. The range of difficulties of the imagined movements included difficulty contexts that were within (Experiment 1) or outside (Experiment 2) the range of difficulty experienced during execution. It was found that imagined movement times of movements within the range of movement difficulties experienced were more consistent with Fitts' Law after movement experience, whereas imagination of more difficult movements was not altered by experience. It is suggested that execution did not enhance imagination of more difficult movements because the relative contributions of motor planning and control to the more difficult movements were different from those in the experienced movements. Thus, the enhancement of imagination through experience might only occur when mechanisms underlying the executed and imagined movements are similar.

1. Introduction

Imagining a simple action, such as picking up a glass, is closely related to executing that same action, with the exception that motor output is absent. Indeed, Decety and Jeannerod (1995) defined motor imagery as a "dynamic state during which a subject mentally simulates a given action" (p. 127). Converging evidence from several sources indicate that many of the principles associated with action execution also pertain to motor imagery (Jeannerod, 1995, 2004). For example, past research has revealed that motor imagery and execution involve activation of very similar cerebral structures (Crammond, 1997; Jeannerod, 2001; Sirigu et al., 1995). These similarities have led some researchers to hypothesize that a common ideomotor network may underlie the processes of action execution and imagination, and maybe even perception (Hommel, 2009; Jeannerod, 2001; Prinz, 1997). In this ideomotor approach, it is hypothesized that the neural codes that are responsible for generating actions are tightly coupled with the neural codes that represent the perceptual consequences of that action (for reviews see Hommel, 2009; Prinz, 1997; Shin, Proctor, & Capaldi, 2010). In action imagination, these neural codes are run at a sub-threshold level such that individuals can effectively simulate a given action via the thought or perception of its perceptual effects (Grosjean, Shiffrar, & Knoblich, 2007; Jeannerod, 2001). It is this common ideomotor network that may link the processes of action execution, imagination and perception.

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Furthermore, the coupling or binding of action and effect codes is suggested to occur through experience and/or training. Once these corresponding codes are integrated, the activation of one code will lead to the excitation of the other (Shin et al., 2010). Elsner and Hommel (2001) demonstrated this action-effect integration through experience across a series of studies. During the training phase of one task, the researchers had participants perform a choice reaction time task in which they made arbitrary left and right keyboard presses. A specific effect tone followed each response – a high tone followed a left key press and a low tone followed a right key press. It was predicted that the constant pairing of a response with an effect tone would lead to binding between that specific response and a specific tone. Following the training, subjects were presented with a free-choice task where the effect tones were randomly presented prior to the moment in which the participant was to choose to execute a left or right key press. The critical finding of the studies was that participants were more likely to choose and execute a compatible response to the task-irrelevant tone effects. That is, left key responses were made more often after a high tone and right key responses were made more often following a low tone was presented. The authors concluded that this finding indicated that participants formed an association between the codes for the motor pattern underlying the action and the perceptual code representing the consequence of the action, lending support for a bidirectional relationship between actions and their perceptual effects. Comparable effects of action-effect binding have been reported for visual (Kunde, 2001), temporal (Kunde, 2003), semantic (Koch & Kunde, 2002), and other relations between actions and effects.

Similar training effects have been observed or intuited from studies of action imagination and execution in aiming movements. In these behavioral studies, paradigms exploiting Fitts' law have been utilized because this equation accurately characterizes the speed-accuracy trade-off that occurs during rapid aiming movements and, hence, provides a solid platform upon which to form predictions. Fitts' law describes the logarithmic relationship between the speed and accuracy of movements as a function of the difficulty of the movement (Fitts, 1954). Specifically, while performing a reciprocal pointing task, participants increase their movement times (MTs) to maintain accuracy and precision across movements of increasing difficulty. This speed-accuracy relationship can be described by the formal equation: $MT = a + b\left(\log_2 \frac{2A}{W}\right)$, where a and b are constants related to an individual's base MT and the unit increase in difficulty as function of movement difficulty, respectively. The $\left(\log_2 \frac{2A}{W}\right)$ component of the equation quantifies the difficulty of the movement, and has been termed the index of difficulty (ID). This ID is related to the width of the target (W) and the movement amplitude (A) (centre-to-centre distance between the targets). Effectively, as either movement amplitude increases or target width decreases, actors need to increase their MTs to maintain accuracy.

This speed-accuracy trade-off has been observed in imagined movements as well. For instance, Sirigu et al. (1995) had a patient with a unilateral lesion of the motor cortex both execute and imagine moving a pen back and forth between a starting position and a target. Critically, the target width was manipulated in accordance with Fitts' law. They found that executed and imagined MTs were linearly related to ID, conforming to Fitts' law (see also Decety & Jeannerod, 1995). Most interestingly, motor imagery was impaired for the same movements which the patient had difficulties executing overtly. In neurotypical adults, Fitts' speed-accuracy trade-off has consistently been shown in imagined pointing movements (Cerritelli, Maruff, Wilson, & Currie, 2000; Macuga, Papailiou, & Frey, 2012; Papaxanthis, Schieppati, Gentili, & Pozzo, 2002; Young, Pratt, & Chau, 2009) and, more recently, researchers have revealed accuracy-dependent activation of the right cerebellum and superior parietal lobule when imagining a Fitts'-type task (Lorey et al., 2010). These results provide evidence that Fitts' law is present in imagined movements. On the larger theoretical level, the presence of Fitts' law in imagined movements and, in particular, the similarity in imagined and executed MTs is consistent with an ideomotor account of action imagination. The similarity in imagined and executed MTs is consistent with the ideomotor account because, according to this account, the same action-effect codes that enable execution are also engaged at a sub-threshold level during action imagination.

More recently, Wong, Manson, Tremblay, and Welsh (2013) conducted a further testing of the ideomotor account by investigating the relationship between action execution and imagination of a reciprocal aiming task.[1] Consistent with previous work, these authors used MT as a common measure of actual and imagined movements. In addition to assessing the relationship between execution and imagination, the study was designed to examine the effect that execution (i.e., task experience) had on imagined MTs. To achieve this latter goal, participants performed the action imagination task before and after executing the same movements. Based on previous work showing that executing a movement and experiencing the perceptual consequences of the movement enhances the association between the codes representing them (e.g., Elsner & Hommel, 2001; see also Heyes, 2001), they predicted that motor experience should lead to a refinement of the action and effect codes and an enhancement of the link between those codes. The consequence of these refinements and enhancements would be that MTs in the imagination task would be more similar to actual execution MTs following task experience. The critical finding of the study was that imagined MTs were indeed more similar to execution MTs after experience with the aiming task. A control group who completed a non-aiming task in between imagination sessions did not show a change in imagined MTs suggesting that time, repeated experience with the imagination and perception tasks, and motor system activation was not responsible for the change in MTs. The authors suggested that the reduction in imagined MTs following task experience was due to enhanced action-effect binding, specific to the experience with the task. Specifically, it was thought that the tighter coupling of action and effect codes (brought about via experience) meant that participants could more effectively and realistically simulate actions that were closer to their actual MTs. This enhanced imagination resulted in an imagination experience

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[1] Note that action perception was also examined this Wong et al. (2013) study. Because the present research focuses on imagination, the results of the perception task will not be discussed further. It should be noted, however, that the results for the perception task were consistent with those of the action imagination task and, as such, supported the hypothesis that a common representational network underlies action execution, imagination, and perception. Please read Wong et al. (2013) for more details.

that was more temporally similar to actual execution. This result highlights the importance of motor experience for action imagination and implicates the ideomotor theory as the basis for an account of the change in imagined MTs following this experience.

In a follow-up study, Yoxon, Tremblay, and Welsh (2015) tested if improvements in action imagination following task experience are specific to the task. Using the same reciprocal aiming task as Wong et al. (2013) for the imagination task, Yoxon et al. assessed changes in imagined MTs between two groups who either executed (experienced) the same reciprocal aiming task as in the imagination task or a discrete aiming task with comparable speed-accuracy (ID) demands. The two groups completed different tasks with similar demands because reciprocal and discrete aiming movements are known to have different and distinct movement patterns. Specifically, reciprocal aiming movements require a reversal movement at the point of contact with each target, whereas discrete aiming movements do not have a reversal and consist of only one unit of movement. This difference results in a differing pattern of antagonistic muscle activity and differing patterns of neural activation (Schaal, Sternad, Osu, & Kawato, 2004). The authors predicted, therefore, that if changes in imagined MTs are due to a refinement between event-specific codes for perceptual task consequences and the motor codes for that particular task, then pre/post changes in MTs should only be seen when participants experience the reciprocal aiming task (same as imagination) and not when they experience the discrete task. Consistent with this prediction, it was found that imagined MTs approached actual execution MTs for the group of individuals that experienced the reciprocal aiming task to a greater extent than for the group that executed the discrete aiming task. Because the changes in imagined MTs in this experiment were found to be task-specific, this result suggests that task experience must elicit a binding of perceptual effects and motor patterns, in a way that is task or event specific, which is in line with ideomotor principles and the ideomotor account of imagination.

The purpose of the present work was to further investigate the influence of movement experience on imagination by assessing the context-specific effects of execution on imagination. Specifically, the main research question involved determining if experience executing reciprocal aiming movements in one set of movement difficulty contexts affected the strength of the relationship between speed and accuracy (Fitts' law) for imagined movements in non-experienced movement difficult contexts. Yoxon et al. (2015) found that executing one type of movement did not influence imagination of different movements in similar contexts (i.e., with comparable accuracy demands), whereas the present study examined whether or not experience executing movement in one set of contexts influences the imagination of the same type of movements in different contexts. Here, the context was defined by the difficulty of the movements.

To evaluate the potential transfer of task experience to non-executed movements, the imagined movements were completed in contexts that included movement difficulties that lie within (Experiment 1) and beyond (Experiment 2) the range of IDs experienced in execution using combinations of target width and movement amplitude that were and were not experienced. In Experiment 1, participants imagined movements between IDs 2 and 4, but only experienced movement difficulties of 2 and 4. In Experiment 2, participants imagined movements between IDs 2 and 6, but only experienced movements at IDs of 2, 3 and 4. This distinction in IDs between experiments is of particular importance because there appears to be a shift in the relative contribution of planning and control processes used in reciprocal aiming movements at high IDs (ID > 4). Specifically, planning and control processes for reciprocal movements at IDs > 4 have planning and control processes that are more similar (although not identical) to those used for discrete movements than reciprocal movements of lower difficulty (ID < 4) (Buchanan, Park, & Shea, 2006). Thus, action-effect codes for reciprocal movements at various IDs below 4 might be similar, whereas those for reciprocal movements above 4 may not be very similar to those for reciprocal movements below 4. In some ways, therefore, the contrast between experiments in the current experiment is similar to the contrast between the different task groups in Yoxon et al. (2015) even though the movement type (reciprocal) is consistent in the present work.

Based on these premises, it was predicted that imagined movements that are more similar to those experienced would see the greatest change following experience. In line with the findings of previous research (Wong et al., 2013; Yoxon et al., 2015) these changes following experience were predicted to include a decrease in imagined MT such that the imagined MTs might be more similar to actual MTs. The imagined MTs of non-executed movements in Experiment 1 were expected to be affected (be more similar to MTs expected for executed movements) following experience. Therefore, it was predicted that there would be a decrease in MT and/or a change in the relationship between MT and ID following experience. In contrast, because the non-executed movements in Experiment 2 were more difficult than those that were experienced and are likely generated by action-effect codes that are different from those that were experienced, the imagined MTs at the more difficult non-executed IDs were not predicted to be altered by the experience (the MTs would not be more similar to those expected for executed movements). On the other hand, if simply experiencing the actual pattern of the executed reciprocal movement is sufficient to enhance imagination across a range of non-executed movements, then the imagined MTs at the non-executed IDs will be altered by the experience in both experiments.

2. Experiment 1

The purpose of Experiment 1 was to investigate whether the effects of action execution on the accuracy of imagined MTs can be transferred to reciprocal aiming movements that are not actually executed, but whose ID lies within those movements that were executed. In other words, it was determined whether or not participants could successfully interpolate imagined MTs based on experience with aiming movements that have IDs that are greater or lesser than those imagined.

2.1. Methods

2.1.1. Participants

Sixteen right-handed individuals (6 men and 10 women) aged 18–34 years participated in the study and received monetary compensation for their time. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study. Handedness was determined by self-report. All participants were right hand dominant. Participants provided informed consent and the procedures of the study were approved by the Office of Research Ethics at the University of Toronto.

2.1.2. Design, apparatus and tasks

The design of the current study was based on the studies of Wong et al. (2013) and Yoxon et al. (2015). In the action execution task, participants completed a series of aiming movements on a set of six posters. Each poster consisted of a pair of identical black target strips pasted onto a white poster board (57 cm [l] × 72.5 cm [w]). The targets were all 15 cm in length and one of three different widths (2, 4 or 8 cm). The distance between the targets varied (4, 8, 16, 32 or 64 cm), generating three posters with ID of 2 and three posters with an ID of 4. In the imagination task, a total of ten posters were used: the same six posters used in the execution task plus four posters not used in the execution task. Four new combinations of target width (2 or 3 cm) and amplitude (12 or 8 cm) were used to generate two posters with an ID of 3 (3 cm [w] × 12 cm [a] and 2 cm [w] × 8 cm [a]), one with an ID of 2.4 (3 cm [w] × 8 cm [a]) and one with an ID of 3.6 (2 cm [w] × 12 cm [a]). These additional posters were created with these specific combinations because they involved widths and amplitudes that were and were not specifically used in the execution task. For example, a poster with a combination of a 3 cm target with a 12 cm amplitude represents an entirely unique combination (neither a 3 cm target nor a 12 cm amplitude were used in the execution task), whereas a poster with a 3 cm target and an 8 cm amplitude uses a unique target width but an amplitude that would be experienced in the execution task. The combination of unique and non-unique widths and amplitudes were used to separate the effects of experience with a specific movement width or amplitude alone. The various combinations of target width and movement amplitude used in imagination and execution for this experiment are illustrated in Table 1.

2.1.2.1. Execution task.
Participants sat in front of a table in view of an optoelectric motion tracking system (Optotrack Certus, Northern Digital Inc.). An infrared emitting diode (IRED) was attached to the participant's right index finger. One of the six poster boards was clamped onto the table in front of the participant. The order of the presentation of the posters was randomized. Beginning with their right index finger on the right side target, the participants were asked to move as quickly and accurately as possible between the two targets, ten times (i.e., one movement was from the right to the left target and the next was from the left to the right target). Participants only executed movements between target combinations with an associated ID of 2 and 4. Participants executed three sets of ten movements for each of the six poster boards.

2.1.2.2. Imagination task.
The imagination task was consistent with the execution task, in that, prior to the imagination, participants began with their right index finger on the right side target. They were then asked to imagine themselves moving as quickly and accurately as possible between the two targets, ten times. Following a verbal "go" signal from the experimenter, participants signalled the beginning of the imagination by lifting their finger approximately 15 cm off the poster board. To signal the end of the imagination of the movements, participants placed their finger back on the right side target. Participants were instructed to time the lift of their finger so that it was simultaneous with the imagined lifting of the finger from the right target and to time the placement of the finger back on the target with the end of the last imagined movement. Participants performed three consecutive imaginations of 10 movements with each of the 10 poster boards. The order of the posters was randomized.

2.1.3. Procedure

Participants were tested individually. All participants completed the imagination task twice, once before and once after completing the execution task. The three tasks (pre-execution imagination, execution and post-execution imagination) were completed in a single fifty-minute session.

Table 1
Target widths and movement amplitudes (amp) for all posters used in Experiment 1. Participants imagined moving to all combinations of target width and movement amplitude. Target widths and movement amplitudes that are entirely unique (non-executed) are italicized. All measurements are in cm.

ID	Executed				Non-executed					
	2		4		2.4		3		3.6	
	Width	Amp	Width	Amp	Width	Amp	Width	Amp	Width	Amp
	2	4	2	16	*3*	8	*3*	*12*	2	*12*
	4	8	4	32			2	8		
	8	16	8	64						

2.1.4. Data collection and reduction

In both tasks, the 3D coordinates of the IRED were recorded by the motion-tracking camera at 250 Hz for 10 s for each trial. The data were stored for offline analysis using a custom analysis program to calculate MTs using Matlab (The Mathworks Inc.). IRED position data were differentiated using a three-point central finite difference algorithm to obtain the instantaneous velocity of movement. The start and the end of the movement sequence in the execution and imagination tasks were identified as the first sample in which instantaneous velocity was below or above 30 mm/s for 100 ms (number of samples = 25), respectively. Average MTs were calculated by dividing the total time of the executed or imagined movement sequence by ten. No movements landed outside the target boundaries and, as a result, no individual MTs were eliminated due to aiming errors. One execution trial from one participant was removed from the data set due to an apparent recording error. Two participants were removed from the data set because the participants admitted to not following the task instructions. Mean MTs for the different combinations of target width and movement amplitude for the execution and imagination tasks were calculated for each individual and were submitted to a series of specific analyses to address the experimental hypotheses, as outlined in the following section.

2.1.5. Analysis

To determine if MTs in each of the tasks conformed to the speed-accuracy trade-off described by Fitts' law, a linear regression and Pearson's correlation coefficient were calculated between group mean MTs (for each of ten posters in the imagination task and each of six posters in the execution task) and ID. The presence of Fitts' speed-accuracy trade-off in executed MTs is a measure of the validity for the action execution task. In the imagination task, the presence of Fitts' law would demonstrate that participants' imagined movements are similar to that of actually executed movements. As such, the presence of Fitts' law in imagined movements is a measure of the temporal congruency between real and imagined movements overall.

Following this initial regression analysis, it was determined if and how imagined MTs differed before and after execution by comparing the slopes and intercepts of the regression lines. The comparison of the slope of the lines is a measure of the similarity of the relationship between imagined or actual MT and the ID of the reaching task. More specifically, this analysis compared the unit increase in MT for each unit increase in ID across the three tasks in the experiment. The comparison of the intercepts of the lines, on the other hand, is the comparison of the participants' base MT across the three tasks.

Finally, to analyze the pre/post changes in imagined movement times for the four combinations of target width and amplitude that were not executed alone, mean pre- and post-execution imagined MTs were submitted to a 2 (Time: Pre, Post) × 2 (Amplitude: Non-executed, Executed) × 2 (Width: Non-executed, Executed) repeated measures ANOVA. This analysis also determined if experience of amplitude or width alone was a factor for changes in imagined MT.

2.2. Results

2.2.1. Initial linear regression analysis

MTs were significantly correlated with ID in each of the tasks: pre-execution imagination, $r = 0.84$, $p < 0.01$, MT = 240.6 + 58.52 (ID); execution, $r = 0.87$, $p < 0.05$, MT = 127.4 + 57.52 (ID); post-execution imagination, $r = 0.92$, $p < 0.001$, MT = 197.2 + 39.47 (ID). Thus, MTs in each task conformed to Fitts' law.

Consistent with previous work (e.g., Wong et al., 2013; Yoxon et al., 2015), it was found that the slopes of the regression lines in all tasks did not significantly differ, $F(2,20) = 0.86$, $p = 0.44$. The intercepts of the pre- and post-execution lines, on the other hand, were significantly different, $F(1,17) = 69.79$, $p < 0.0001$, revealing lower imagined MTs following task execution than before task execution. Additionally, the intercept of the regression line for pre-execution imagination was significantly greater than that of actual execution $F(1,13) = 41.36$, $p < 0.0001$, and there was no significant difference in the intercepts of the lines between post-execution
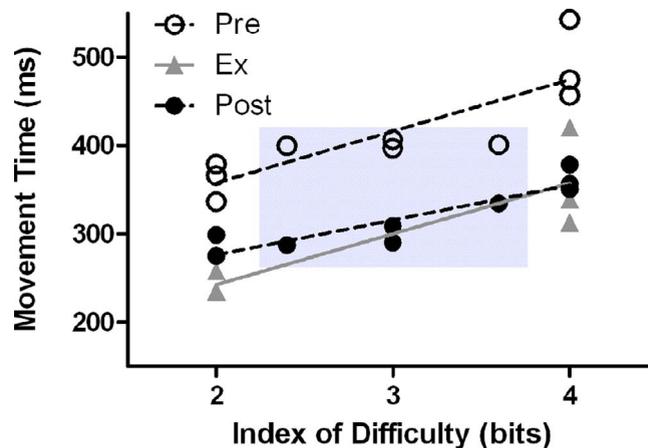

Fig. 1. Group mean imagined and actual movement time and their associated linear regression lines, as a function of index of difficulty (ID) for all three tasks for Experiment 1. Data points for the non-experienced movements are highlighted in the light grey box.

imagination and actual execution, $F(1,13) = 1.25$, $p = 0.29$. This pattern of findings indicates that post-execution imagined MTs were more similar to actual execution MTs than the MTs in the pre-execution imagination task (Fig. 1).

2.2.2. Analysis of non-executed imagined movements

The ANOVA analysis revealed a significant effect of Time, $F(1,13) = 30.60$, $p < 0.0001$, $\eta_p^2 = 0.702$, indicating that MTs in the post-execution task were shorter than in the pre-execution task. There was also a significant time by width interaction, $F(1,13) = 6.45$, $p < 0.05$, $\eta_p^2 = 0.33$. Bonferroni-corrected paired-samples t-tests revealed that while there was no difference between executed and non-executed widths in the pre-test, $t(27) = 0.36$, $p = 0.725$, MTs for the non-executed widths were significantly lower that than MTs for the executed widths in the post-test, $t(27) = 3.62$, $p < 0.01$.

2.3. Discussion

Overall, the data from Experiment 1 indicate that experience executing movements enhances the imagination of both experienced and non-experienced movements, even when those specific combinations of target width and movement amplitude were not actually performed. This conclusion is supported by the significant reduction in imagined MTs overall and the results of the ANOVA on imagined MT. Interestingly, there was a greater reduction in imagined MT for the non-experienced target width (3 cm) compared to the experienced target width (2 cm). A greater reduction in MT for the non-experienced width than for the experienced width makes sense because the larger target with of 3 cm would lead to a lower ID, and hence shorter MTs, than for the experienced smaller target of 2 cm. Hence, this interaction is consistent with the prediction that experience would enhance the similarity between imagination and execution. Overall, the results indicate that movement experience at IDs 2 and 4 seems to have influenced imagination of movements that fall within these difficulties, despite not having experienced them directly.[2]

3. Experiment 2

To further explore the effects of recent task experience on imagined MTs, Experiment 2 was conducted to determine if experience-based changes in MT could be extended to reciprocal movements that were in a more difficult movement context than those that were experienced. In other words, it was determined whether or not participants could successfully extrapolate imagined movements, based on experience with aiming movements that have IDs that are lower than those that are imagined.

3.1. Methods

3.1.1. Participants

A different set of 16 participants (3 men and 13 women) aged 18–34 years old (mean age = 23) completed the study and received monetary compensation for their time. All participants were right handed, had normal or corrected-to-normal vision and were naïve to the purpose of the study. Handedness was determined by self-report. Participants provided informed consent and the procedures of the study were approved by the Office of Research Ethics and the University of Toronto.

3.1.2. Design, apparatus and tasks

The design of Experiment 2 was consistent with that of Experiment 1 in that participants completed both action execution and imagination tasks. In the action execution task, a set of nine posters were used. Each poster consisted of a pair of identical black target strips pasted onto a white poster board (57 cm [l] × 72.5 cm [w]). The targets were all 15 cm in length and one of three different widths (2, 4 or 8 cm). The distance between the targets varied (4, 8, 16, 32 or 64 cm), generating three posters with IDs of 2, 3 and 4. In the imagination task, a total of thirteen posters were used: the same nine posters used in the execution tasks plus four posters not used in the execution task. Four new combinations of target width (2 or 3 cm) and amplitude (48 or 64 cm) were used to generate one poster with an ID of 5 (3 cm [w] × 48 cm [a]), one with an ID of 5.4 (3 cm [w] × 64 cm [a]), one with an ID of 5.6 (2 cm [w] × 48 cm [a]), and one with an ID of 6 (2 cm [w] × 64 cm [a]). These additional posters were created with these specific combinations because they involved widths and amplitudes that were and were not specifically used in the execution task. For example, a poster with a combination of a 3 cm target width and 48 cm amplitude represents an entirely unique combination, whereas a poster with a 2 cm target and 48 cm amplitude uses an experienced target width but amplitude that is completely unique. The various combinations of target width and movement amplitude used in imagination and execution for this experiment are illustrated in Table 2.

3.1.2.1. Execution and imagination tasks.
Both the execution and imagination tasks were completed as described in Experiment 1, with the exception of the indexes of difficulty used, as described in the preceding section.

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[2] Additional analysis revealed that while there were no significant relationship between MT and ID (likely due to the limited number of data points) in either pre- or post-execution imagination, there was a large numerical increase in the correlation coefficients from pre- to post-execution ($r_{pre} = 0.13$, $r_{post} = 0.89$), demonstrating a potential change in the Fitts' law relationship for these points individually.

Table 2

Target widths and movement amplitudes (amp) for all posters used in Experiment 2. Participants imagined moving to all combinations of target width and movement amplitude. Target widths and movement amplitudes that are entirely unique (non-executed) are italicized. All measurements are in cm.

ID	Executed						Non-executed							
	2		3		4		5		5.4		5.6		6	
	Width	Amp	Width	Amp	Width	Amp	Width	Amp	Width	Amp	Width	Amp	Width	Amp
	2	4	2	8	2	16	*3*	*48*	*3*	64	2	*48*	2	64
	4	8	4	16	4	32								
	8	16	8	32	8	64								

3.1.3. Procedure

The experimental procedure was consistent with that of Experiment 1 in that all participants completed the imagination task twice, once before and once after completing the execution task. The three tasks (pre-execution imagination, execution and post-execution imagination) were completed in a single sixty minute session.

3.1.4. Data collection and reduction

The analysis procedures used in Experiment 1 were also used in Experiment 2. No movements landed outside the target boundaries and so no individual MTs were eliminated due to aiming errors. Two participants were removed from the data set. One participant was removed because they did not follow the task instructions. A second participant was removed due to apparent recording errors in that participant's data set. Of the remaining data, one execution trial and one pre-execution imagination trial each from different participants were removed from the data set due to apparent recording errors. Mean MTs for the different combinations of target width and movement amplitude for the execution and imagination tasks were calculated for each individual and were submitted to a series of specific analyses to address the experimental hypotheses, as outlined in the following section.

3.1.5. Analysis

The analysis protocol completed for Experiment 2 was identical to that of Experiment 1. Initially, a linear regression and Pearson's correlation coefficient were calculated between group mean MTs (for each of the thirteen posters in the imagination task and each of the nine posters in the execution task) and ID to determine if MTs conformed to Fitts' speed-accuracy trade off. Following this initial analysis, the slopes and intercepts of the regression lines were compared to determine if and how imagined MTs differed following execution. Finally, the MTs for the non-executed imagined movements were submitted to a 2 (Time: Pre, Post) × 2 (Amplitude: Non-Executed, Executed) × 2 (Width: Non-Executed, Executed) repeated measures ANOVA.

3.2. Results

3.2.1. Initial linear regression analysis

MTs were significantly correlated with ID in each of the tasks: pre-execution imagination, $r = 0.87$, $p < 0.001$, MT = 221.3 + 39.32 (ID); execution, $r = 0.82$, $p < 0.01$, MT = 90.69 + 64.18 (ID); post-execution imagination, $r = 0.95$, $p < 0.001$, MT = 144.4 + 45.09 (ID). Thus, MTs in each task conformed to Fitts' law.[3]

Consistent with Experiment 1, the slopes of the regression lines in all tasks did not significantly differ, $F_{(2,29)} = 1.46$, $p = 0.25$. The intercepts of the pre- and post-execution lines did, however, significantly differ, $F_{(1,23)} = 26$, $p = < 0.001$, suggesting lower imagined MTs following task execution than before execution. Furthermore, the intercept of the regression line for pre-execution imagination was significantly greater than that of actual execution $F_{(1,19)} = 8.98$, $p < 0.05$, and there was no significant difference in the intercepts of the lines between post-execution imagination and actual execution, $F_{(1,19)} = 0.20$, $p = 0.19$ (Fig. 2). These results are similar to those of Experiment 1 and previous work (e.g., Wong et al., 2013).

3.2.2. Analysis of non-executed movements

The ANOVA revealed a main effect of amplitude, $F_{(1,13)} = 19.01$, $p < 0.001$, $\eta_p^2 = 0.594$, wherein imagined MTs for the unique amplitude (48 cm) were overall shorter (M = 393, SD = 147) than the amplitude that was previously experienced (64 cm) (M = 433, SD = 158) – a finding consistent with Fitts' law. The main effect for target width, however, it did not reach statistical significance, $F_{(1,13)} = 4.44$, $p = 0.055$, $\eta_p^2 = 0.255$. Of greater theoretical importance, there was no significant effect of time, $F_{(1,13)} = 3.40$, $p = 0.088$, $\eta_p^2 = 0.208$, and no time by width interaction, $F_{(1,13)} = 0.581$, $p = 0.46$, suggesting that the execution of movements did not significantly influence the post-execution imagined MTs of the extrapolated combinations of target width and

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[3] Although the correlation between MT and ID may seem numerically smaller for the execution condition than the pre-test and post-test imagination conditions, Hotelling's t-test reveals that the correlation between MT and ID for the execution condition does not significantly differ from that for the pre-test, $t(9) = 0.112$, $p > 0.05$, or post-test condition, $t(9) = 1.83$, $p > 0.05$.
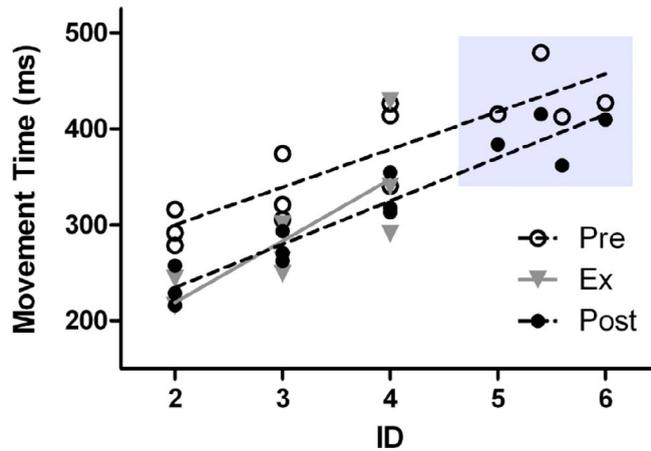
Fig. 2. Group mean imagined and actual movement time and their associated linear regression lines, as a function of index of difficulty (ID) for all three tasks, for Experiment 2. Data points for the non-experienced movements are highlighted in the light grey box.

amplitude. This result stands in contrast to the results of Experiment 1, where there was a significant effect of experience on imagined MT for non-executed imagined movements.[4] Thus, the imagined MTs of non-experienced combinations of target width and amplitude that were within the range of those that were executed (Experiment 1) were more consistent with the MTs expected during execution after experience, whereas the imagined MTs for combinations outside those that were experienced were not.

3.2.3. Between-experiment analysis

To better determine if there are any differences in the influence of experience on the imagination of non-executed movements (i.e., between-experiment differences in the patterns of effects), we assessed and compared the similarities between the imagined MTs for non-executed IDs and the "executed" MTs that would be predicted by the Fitts' equation for those IDs. The first step in this analysis involved calculating the predicted "execution" MTs for the non-executed IDs. In this first step, the MTs for the executed movements at the executed IDs were submitted to a linear regression. A separate regression was performed for each individual participant to obtain the parameters of each individual participant's speed-accuracy trade-off as calculated by Fitts' law. In the second step, the amplitude and width of each target combination were inputted into each individual's regression equation to obtain a predicted execution MT for each of the combinations of target width and amplitude that were not executed. Thus, at the end of the second step, we obtained the MT that was predicted to have emerged for the non-executed IDs if the participants had executed movements at those IDs.

In the final step, difference scores were calculated between the execution MTs for the non-executed movements as predicted by Fitts' law and the MTs obtained for these MTs in the imagination task both before and after the execution phase. Again, separate difference scores were obtained for each individual participant. The absolute value of this difference between the actual imagined MT and the predicted "execution" MT was then used as an index of how similar (or how dissimilar) the imagined MTs were to the MTs that each individual would be predicted to execute based on their actual performance at other IDs. These difference scores were then averaged across the IDs and submitted to a 2 (Experiment: 1, 2) by 2 (Time: Pre-, Post-execution) mixed ANOVA with Experiment as a between-subjects factor and Time as a repeated measures factor.

The ANOVA on difference scores between the executed and the pre/post imagined MTs revealed no significant main effect of Time, $F(1,26) = 0.17$, $p = 0.67$, $\eta_p^2 = 0.006$, or Experiment, $F(1,26) = 2.84$, $p = 0.10$, $\eta_p^2 = 0.098$. There was, however, a significant Time by Experiment interaction, $F(1,26) = 39.03$, $p < 0.001$, $\eta_p^2 = 0.60$, indicating that there was a difference in the patterns of effects from pre- to post-execution imagination for the two experiments. The nature of this significant interaction was assessed using a series of t-tests (Bonferroni corrected to $p < 0.017$).

The first relevant finding was that there was not a statistically significant difference in the pre-execution imagination between the two experiments, $t(26) = 1.49$, $p = 0.15$. Thus, the participants in the two experiments had similar levels of discrepancy between imagined and predicted execution MTs before the execution phase. Comparisons of the imagined MTs before and after execution for Experiment 1 revealed that there was a significant decrease in the difference scores after execution, $t(13) = 4.77$, $p < 0.001$, indicating that participants' imagination MTs were significantly more similar to the predicted execution MTs following execution. The same set of comparisons for the difference scores from pre- to post-execution in Experiment 2 revealed a significant pre/post-execution *increase* in the difference scores, $t(13) = 4.07$, $p = 0.001$, indicating that similarity between the participants' imagination MTs an execution MTs did not improve (and may have even declined) following execution (Fig. 3). Therefore, imagined MTs of the non-executed movements were more closely aligned with actual execution MTs following the execution experience in Experiment 1. This was not the case for Experiment 2.

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[4] Additional analysis revealed that there was once again no significant relationship between MT and ID for either the pre- or post-execution imagination and that the numerical difference in the correlation coefficients from the pre-to post-execution imagination was much smaller than that for Experiment 1 ($r_{pre} = -0.19$, $r_{post} = 0.25$), suggesting that the magnitude of the change in the Fitts' law relationship for the non-executed points was much smaller than that seen in Experiment 1.
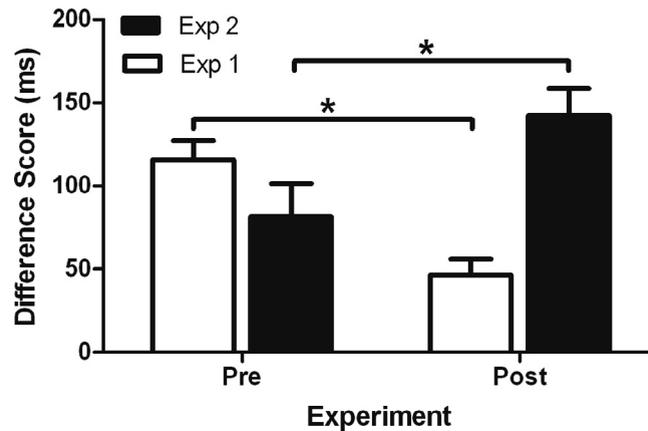
Fig. 3. Group mean difference scores between predicted actual movement time and imagination movement time for non-experienced movements for Experiment 1 and Experiment 2. An asterisk denotes a significant difference at the $p = 0.017$ level.

3.3. Discussion

Overall, the data for Experiment 2 indicate that the imagination of movements that were more difficult to perform than those that were executed were not more similar to actual movements after experience. This conclusion was initially supported primarily by the absence of a significant pre/post-experience decrease in imagined MTs in Experiment 2, but is reinforced by the series of between-experiment comparisons. This pattern of results stands in contrast to Experiment 1, where there was a reduction in imagined MTs from pre- to post-execution. In Experiment 2, although there was an overall reduction in imagined MT from pre- to post-execution, this effect was not seen in the non-executed IDs when they were considered alone.

4. General discussion

The purpose of the present study was to investigate how the effect of task experience on imagined aiming movements extends to non-experienced movements that are the same movement type, but that vary in the similarity of movement patterns. To answer this question, the two experiments described here were designed to evaluate whether physical experience with reciprocal aiming movements at a set level of accuracy could increase the similarity in MT between actual movements and imagined movements for targets that are within or beyond these accuracy demands. Predictions based on the ideomotor account of action imagination were that: 1) there would be an increase in the strength of the relationship between imagined MT and ID after execution experience; and, 2) the more similar the movement patterns between experienced and imagined movements, the more similar imagined MT and actual MT will be following the experience. These predictions were made because task experience is thought to refine and enhance the coupling of task-specific perceptual codes and the motor codes for the given task. With more refined coding and coupling, participants' imagination of perceptual task consequences (for example, visual feedback) will activate a motor simulation that more closely matches that of actual execution.

In line with the above prediction, it was found in both experiments that there was a significant reduction in the intercepts of the linear regression of group mean imagined MTs from pre- to post-execution. Of greater theoretical relevance, it was found that there was a significant effect of time for imagined movements that were not executed in Experiment 1 where the non-executed movements were within the range of IDs that were executed. This effect of time was not seen in Experiment 2 where the non-executed movements were outside the range of IDs that were executed. Essentially, it was demonstrated that, although there was an overall reduction in imagined MT in both experiments, this effect was not consistent across the experiments for the imagined movements that were not executed. This conclusion was supported by the between experiment analysis conducted on difference scores between actual and imagined MT. The pattern of effects will be discussed in two parts: the first part will discuss the overall effect of execution on imagined MT and the second part will focus on the contrasting results between experiments.

4.1. Overall effect of execution on imagined MT

In both experiments, there was a general reduction in MTs of imagined movements indicating that, following physical experience with reciprocal aiming movements, participants imagined MTs were closer to the time necessary to actually complete those movements. This result is consistent with the results of previous work (Wong et al., 2013; Yoxon et al., 2015) and is in line with the notion that bound ideomotor codes are refined through experience with a given task. Specifically, Elsner and Hommel's (2001) two-stage model of action-control denotes that experience with a task leads to the coupling or association of neural codes for an action and the neural codes for the perceived effects of that action. Following the acquisition and refinement of such an association, the coupling can then be used to guide the selection and execution of goal-directed action. Because bound action-effect codes may be run at a sub-motor threshold level in action imagination (as discussed in the Introduction), it is thought that a more refined coding and tighter

binding between an action and its' perceptual effects should elicit imagined movements that are more similar to actual movements. In the current experiment, actual execution of reciprocal aiming movements allowed participants to experience the pattern of movement coupled with its associated perceptual effects (i.e., visual and proprioceptive feedback) and refine the association between the two components. It is this more refined association between action and effect that produces imagined MTs that are closer to actual execution MTs following experience.

It should also be noted that while it is possible that overall decreases in imagined MT could be related to simple motor imagery experience (i.e., imagined MTs are closer to actual MTs because participants have gained experience with the imagination task irrespective of the execution), it is unlikely that this factor accounts for the changes seen in the present study for several reasons. First, changes in the vividness of motor imagery or in motor imagery ability are typically only seen in interventions that take place over extended periods of time (i.e., more than a single session) (for a review on motor imagery training see Schuster et al., 2011). Second, Wong et al. (2013) demonstrated that a control group of participants who imagined themselves performing a reciprocal aiming task before and after executing a non-aiming (key press) motor task did not show a significant pre/post-motor task change in imagined MTs. Furthermore, as discussed in Section 1, Yoxon et al. (2015) demonstrated that there are greater changes in imagined MT when participants execute aiming movements that are the same movement type (i.e., reciprocal vs. discrete) as those imagined, despite experience aiming at comparable accuracy requirements. This result demonstrates that specific task experience is a greater contributor to the observed changes in imagined MT than knowledge of one's own speed-accuracy trade-off or aiming practice alone. Therefore, it is likely that the overall shift in imagined MT towards the actual execution MTs seen in both experiments are driven by the physical experience with reciprocal aiming movements, consistent with the previous literature. Additionally, if the overall changes in imagined MT seen in the present two experiments were an effect of motor imagery experience, time or general motor system activation, then changes in imagined MTs toward actual movement times would have been found for the non-executed movements in both experiments. Overall, the data suggest that the overall reduction in imagined MT is due to task specific action-effect association refinement and not due to the other factors discussed. This notion will be expanded upon in the following subsection.

4.2. Contrasting effects of execution on the imagination of non-executed movements

Although the overall reduction in imagined MT discussed in the previous section is theoretically-relevant, the main unique finding of the present work was the contrast between the experiments in the effects of experience on imagination of non-executed combinations of target width and movement amplitude. When non-executed movements were within the range of IDs of executed movements, there was a significant reduction in imagined MT from pre- to post-execution (Experiment 1). In contrast, there was no significant effect of execution experience for imagined MTs when the non-executed movements were beyond the range of IDs that were executed (Experiment 2). Furthermore, the between experiment analysis on the differences between actual and imagined MTs demonstrated that imagination performance may have actually declined in Experiment 2. Of additional interest, there was a width-specific change in imagined MTs for Experiment 1, that biased a greater decrease in imagined MTs for the non-executed (and wider) target widths, demonstrating that participants changed their imagined MTs after execution experience to be more in line with Fitts' speed-accuracy trade off. A similar effect as not apparent in Experiment 2, suggesting that there were no changes in the imagined speed-accuracy relationship follow execution experience. Together, these findings demonstrate the movement-specific nature of the effect of experience on imagination.

The described pattern of effects may be related to differences in task and motor pattern specificity across the ranges of ID used in these experiments. As previously discussed, it has been suggested that, at higher levels of ID, there may be a transition in control mechanisms and/or units of action in reciprocal aiming movements (Buchanan et al., 2006, for example). That is, it has been suggested that at approximately ID = 4, even though the pattern of movements the actor is executing are still continuous reciprocal movements, the underlying units of action for these reciprocal aiming movements are more similar to discrete units of action. These potential differences in the control processes of reciprocal aiming movements at lower and higher IDs are critical as previous work has demonstrated that the refining of action and effect codes that occurs through experience influences imagined MTs in a way that is task specific. Consequently, it has been suggested that because there are differences in the control and execution of various aiming movements (e.g., reciprocal movements are not simply a concatenation of discrete units); experience with aiming in one context may not lead to more execution-similar internal representations of aiming in another context. This result is consistent with the ideomotor approach to action imagination and execution (Hommel, 2009; Shin et al., 2010) and is closely related to the contrast in results between experiments in the present study. This account of the findings will be expanded in the following paragraphs.

In Experiment 1, participants executed aiming movements at IDs 2 and 4. The non-executed IDs fell between 2.4 and 3.6. In contrast, in Experiment 2 participants executed movements at IDs 2, 3 and 4, but the non-executed IDs fell between 5 and 6. This difference in the IDs used in the experiments is crucial because the majority of experiments that demonstrate transitions in the mechanism of control of reciprocal aiming movements at higher IDs denote these transitions to begin at approximately ID = 4. For example, Buchanan and colleagues demonstrated a transition from continuous to discrete units of action in a reciprocal pointing task within a critical ID range between 4.01 and 4.91 (Buchanan et al., 2006). Essentially, it is thought that at lower difficulties, individuals are able to take advantage of the elastic properties of the muscles and tendons such that they are able to use elastic potential energy that is stored while moving into a reversal movement to initiate movement in the reverse direction (i.e., harmonic motion). At higher levels of difficulty, there seems to be a decrease in the harmonicity of reciprocal aiming movements (as demonstrated by Buchanan et al., 2006). This decrease in harmonicity likely occurs because, at higher IDs, individuals must move with a lower limb velocity just prior to the reversal component of the reciprocal movement (see Guiard, 1993). Therefore, it is likely

that at higher levels of difficulty, there is a transition from continuous (or harmonic) motion to units of action similar to those of discrete aiming movements. This notion has been supported extensively in previous research (Buchanan et al., 2006; Huys, Fernandez, Bootsma, & Jirsa, 2010; Lazzari, Mottet, & Vercher, 2009; Terrier et al., 2011). Importantly, the transition in control described is based on ID, not necessarily the combination of target width and amplitudes that make up the ID. Critically, it is suggested that this transition occurs approximately following ID = 4. This distinction is consistent with the observation here that ID specific experience modulated imagined MTs to both experienced and non-experienced target widths and movement amplitudes.

This transition in planning and control could underlie the differences seen in the pattern of results between the two experiments because participants who were asked to imagine aiming movements that were between IDs 2 and 4 had the opportunity to experience a movement pattern (and its perceptual effects) that was more similar to the non-executed movements at IDs in between these values. As discussed in the previous subsection, the two-phase model of action control put forth by Elsner and Hommel (2001) states that associations between action and their effects are built and refined through action-specific experience. Therefore, a lack of action-specific experience (due to a difference in the control of reciprocal aiming movements at high IDs) can account for the differences seen between Experiments 1 and 2. Although it is possible that there was not an effect of experience on imagined movements at higher IDs because of quantitative differences in ID alone (i.e., the magnitude of the ID), previous work highlighting the task-specific nature of the effects of experience (Yoxon et al., 2015) suggest that qualitative differences in movement pattern and control between lower and higher IDs should not be ignored. Specifically, participants in Experiment 2 imagined a pattern of movement and effects that were not consistent with the movements they executed because the imagined (non-executed) movements were beyond ID = 4 and therefore planned, controlled, and executed in a different way. Consequently, the mismatch in mechanisms of control and units of action in Experiment 2 accounts for the lack of a significant pre-post change in imagined MTs for the movements that were not executed.

5. Summary and conclusions

In summary, the current study examined how refining of action-effect associations through experience with reciprocal aiming movements could enhance the temporal accuracy of the imagination of reciprocal aiming movements that are not actually executed. Experiment 1 revealed that experience can assist in imagining movements that are within the range of movement difficulties experienced, whereas Experiment 2 revealed that imagination of more difficult movements is not enhanced by experience. It is suggested here that differences in patterns of movement between fast reciprocal aiming movements at low IDs and high IDs contributed to the contrast in results between experiments because this contrast presents a mismatch in the movements experienced and the imagined movements that were not experienced. This effect is likely due to an action-specific binding effect in execution which allows for sub-motor threshold activation of bound action-effect representations in action imagination. Finally, this result is consistent with the ideomotor approach to action imagination and may have implications for the use of action imagination in sport and motor rehabilitation. Specifically, it may be crucial for motor imagery to be used in a way that is closely linked to the desired motor outcomes. That is, the data suggest that imaginations of actions rely heavily on our experiences in an action-specific way. Thus, it might be that motor imagery is a more useful tool for rehabilitation when it can be coupled with actual movements, as has already been shown in previous research (see Schuster et al., 2011, for review). When movement is not possible, although motor imagery could still be a useful tool, it may be necessary to find ways to relate imaginations to action-specific pre-injury experiences.

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