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The Effects of Practice and Load on Actual and Imagined Action

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THE EFFECTS OF PRACTICE AND LOAD
ON ACTUAL AND IMAGINED ACTION

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DEDICATION

I dedicate this thesis to my family, for their patience and support.

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I would like to thank my thesis advisor, Dr. Andrew Slifkin. His careful guidance and openness have made this thesis possible. I would also like to thank the Cleveland State University Department of Psychology and the University Transportation Center for their financial support.

THE EFFECTS OF PRACTICE AND LOAD

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ABSTRACT

Research has shown similarities between actual movement durations (AMD) and imagined movement durations (IMD). These similarities are believed to reflect the extent to which an action is represented by an internal model or emulator in the brain. Differences in AMD and IMD could be due to the employment of online feedback processes during actual movement in addition to emulated feedback as suggested by emulation theory. The current study was framed by these basic components of emulation theory. Methodology similar to a study by Papaxanthis, Schieppati, Gentili, and Pozzo (2002) was used to examine AMD and IMD of the arm under different conditions of added load and practice with the hypothesis that AMD and IMD would diverge with practice. The current study replicated the previous findings of a nonsignificant difference between AMD and IMD. As opposed to divergence, the results reveal an independent decrease in AMD and lack of change in IMD over 10 blocks of trials. The results suggest that the lack of change in IMD reflects a process that protects previous learning from catastrophic interference (McCloskey & Cohen, 1989). Other analyses revealed that the variability of IMD was larger than that of AMD but also revealed that the variability of both decreased with practice. It is suggested that both practice and feedback play a role in improving the consistency of a movement’s timing. Significant correlations between AMD and IMD were also found. The results are consistent with the basic components of the emulation model.

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CHAPTER I

INTRODUCTION

Motor imagery is the process by which voluntary movement is rehearsed or simulated in the imagination. Past research involving motor imagery has compared imagined movement to actual movement as a method to discover which aspects of movement are predicted before its execution (Decety & Michel, 1989; Decety, Jeannerod, & Prablanc, 1989). These studies have employed a variety of different tasks including drawing, writing, and walking. This *a priori* knowledge of an action is thought to be represented in the neural circuitry of the brain. Among other similar theories of motor control, the emulation theory of representation (Grush, 2004) provides a general framework under which current problems in motor control research can be understood.

Emulation theory is a hybrid theory that describes human movement by using an internal model and online feedback. Although specific details of emulation theory are unique, in a broader scope, it is similar to other hybrid theories such as those suggested by Wolpert, Ghahramani, and Jordan (1995) or Desmurget and Grafton (2000). Emulation theory was chosen as the experimental framework for this study because it is familiar to the author, and at a general level, it is representative of other hybrid theories.

Emulation theory is born out of control systems, an area in engineering that attempts to control a process through online feedback and internal modeling of the process (see Figure 1). Here is the general idea. First, the goal-state of the plant (i.e. limb) is selected. The controller (central nervous system) then sends a corresponding control signal to the plant. An efferent copy of this command is also sent to the emulator. The emulator transforms the efferent copy into a predicted afferent signal that would be expected as feedback from the actual plant. In this way, the emulator acts as a “pseudo” plant. The predicted afferent signal from the emulator is then compared to the actual afferent signal from the plant. The value that results from this comparison is a correction called the sensory residual. The sensory residual is then run through a filter that may place more emphasis on feedback from the plant or feedback from the emulator, depending on whether the action is unfamiliar or familiar, respectively.

In light of the emulation theory of representation, motor imagery is the process of emulating feedback of a voluntary action in imagination, during the absence of sensory feedback and suppression of the actual control signal (Grush, 2004). Motor imagery can then be used as a tool to understand how actions are represented in the brain and

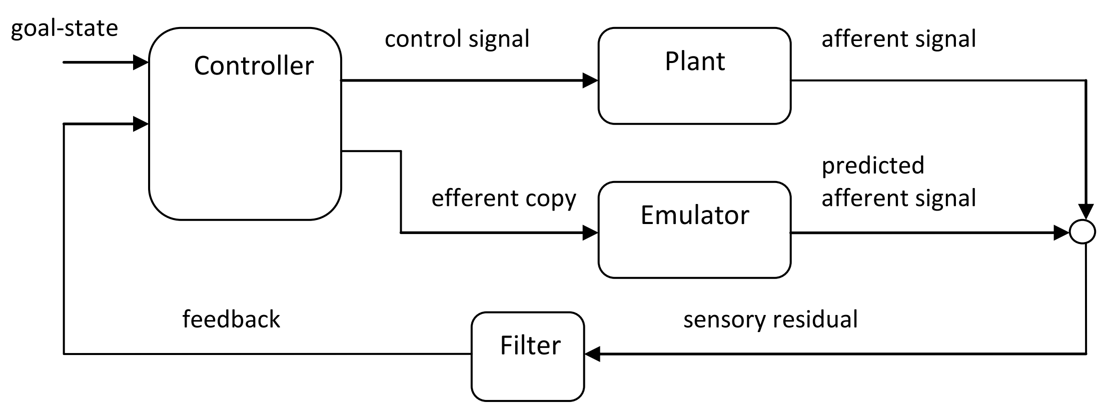

Figure 1. A process model of the emulation theory of representation (Grush, 2004).

understand which aspects of a movement are *anticipated* without actual movement taking place.

Similarities between the timing of motor imagery and actual movement are thought to suggest that the force dynamics involved are accurately emulated or accounted for by an internal model (Papaxanthis, Schieppati, Gentili, & Pozzo 2002; Gentili, Cahouet, Ballay, & Papaxanthis, 2004). The similarity between actual and imagined action has also been supported by neuroimaging studies that reveal common areas of activation, mainly, the primary motor cortex, premotor cortex, and supplementary motor cortex (Porro et al., 1996; Roth et al., 1996; Dechent, Merboldt, & Frahm, 2003).

Discrepancies between actual and imagined movement durations have also been reported (Cerritelli, Maruff, Wilson, & Currie, 2000; Reed, 2002; Calmels, Holmes, Lopez, & Naman, 2006; Slifkin, 2008). Differences arise when the task is particularly complex such as a springboard dive (Reed) or gymnastics routine (Calmels et al.). Novel tasks, such as moving a weighted stylus (Cerritelli et al.), or moving the finger under conditions of heavy load (Slifkin) also yield differing durations. In a golf task, the further participants imagined putting a ball, the longer IMD's were when compared to AMD's (Orliaguet and Coello, 1998). It appears that during imagined movement requiring varying amounts of force, the force and time components of movement are not always accurately emulated.

Although research has examined similarities and differences between AMD and IMD, how they might change concurrently as a result of practice has not yet been studied. When comparing AMD and IMD, most studies have examined movement durations as averages across trials without analyzing potential changes from trial to trial. One such study by Papaxanthis, Schieppati et al. (2002) found AMD and IMD of the arm to be similar at various load levels (0 kg, 1 kg, or 1.5 kg). Implicit in the study was the assumption that actual and imagined movement representations were the same from the outset and that this similarity remained throughout the experiment. Since no analyses of practice effects were reported, the assumption that actual and imagined movement representations were similar throughout trials might be premature. Slight but nonsignificant elevations in IMD over AMD at all load levels suggest that practice effects might have been masked by averaging the durations over all trials (see Figure 2 in Papaxanthis, Schieppati et al., p. 449).

The current study attempts to replicate the study by Papaxanthis, Schieppati et al. (2002) by testing the effects of practice, performance condition (actual and imagined), and load (0 kg, 1 kg, and 1.5 kg) on movement duration of the arm in the sagittal plane.[1] Similar to Papaxanthis, Schieppati et al., it is hypothesized that there will be a significant main effect for load and a nonsignificant elevation of IMD over AMD. To test the assumption that AMD and IMD remain equivalent throughout trials, a new hypothesis, proposes that AMD and IMD should diverge as a function of practice as indicated by a performance condition by practice interaction (see Figure 2).

In addition to slight elevations of IMD over AMD reported in Papaxanthis, Schieppati et al. (2002), the hypothesis of divergence is dictated by an expected decrease in AMD with practice, and the assumption that a change to the internal model would cause a similar reduction in both AMD and IMD. Studies involving learning curves suggest that AMD would likely decrease as a function of practice (Crossman, 1959). If

[1] The study by Papaxanthis, Schieppati et al. included arm movement in the horizontal plane in addition to movement in the sagittal plane. Movement in the horizontal plane is not included in the current study.

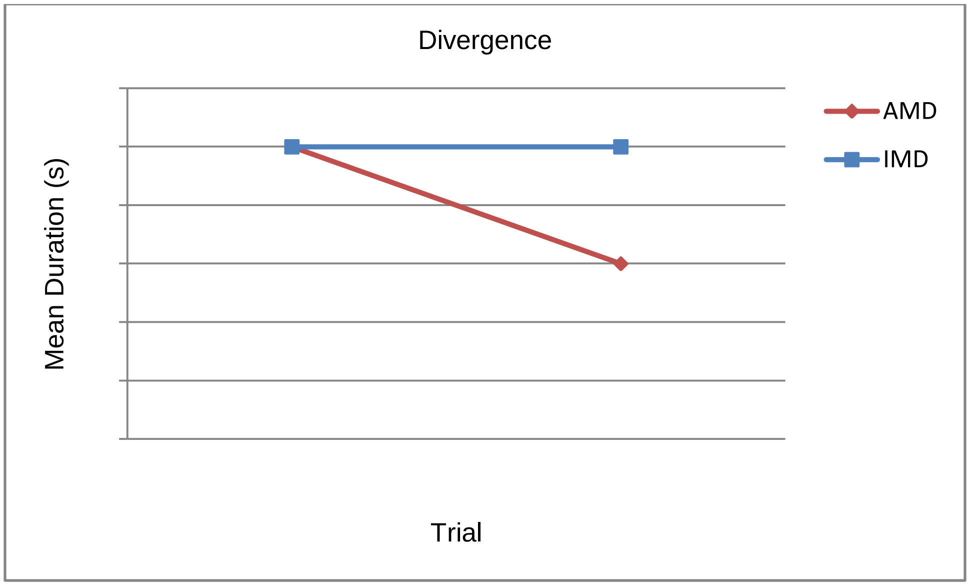

Figure 2. The hypothesis that actual movement duration (AMD) (red) will diverge from imagined movement duration (IMD) (blue) as a function of practice as a result of a decrease in AMD and a lack of change in IMD.

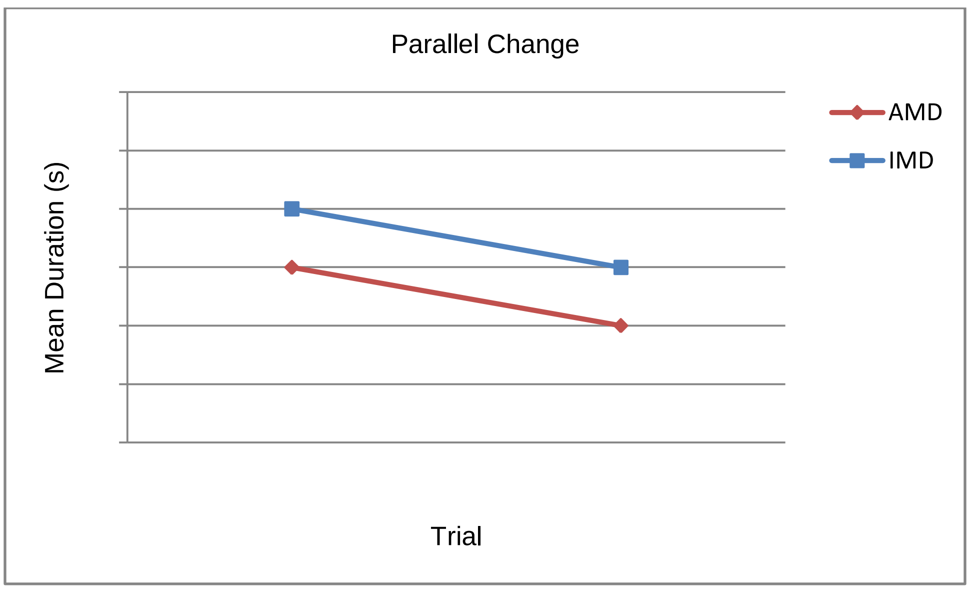

Figure 3. A parallel change in actual movement duration (AMD) (red) and imagined movement duration (IMD) (blue) as a function of practice that might result from a change to the internal model.

we assume that a change to the internal model would cause a similar change in both AMD and IMD, then a change to the internal model cannot result in convergence or divergence because AMD and IMD would change in parallel (see Figure 3). Only a change in the online feedback component of actual action can result in convergence or divergence since such a change presumably could not modify the internal representation and thus, could not influence IMD. Therefore, an expected decrease in AMD implies two possible outcomes. First, AMD and IMD might be similar at the outset and then diverge as a result of a significant decrease in AMD and lack of change in IMD (see Figure 2). The other outcome might be that AMD is longer than IMD at the outset and then converges, also as a result of a significant decrease in AMD and a lack of change in IMD (see Figure 4). Divergence requires IMD to be longer than AMD and convergence requires AMD to be longer than IMD (see Figure 5). Therefore, the slight elevations ofIMD over AMD in Papaxanthis, Schieppati et al. (2002) suggest that divergence will likely occur in the current study. This result is also suggested by Slifkin (2008) in which AMD of the finger decreased without a change in IMD when measured over four trials. Again, since the current study attempts to replicate the results of Papaxanthis, Schieppati, et al. (2002), a nonsignificant main effect for performance condition (AMD vs. IMD) is predicted. A nonsignificant effect for performance condition coupled with the predicted performance condition by practice interaction would suggest that any fixed difference between AMD and IMD is by statistical chance and that only the independent change or lack of change in AMD and IMD is relevant to interpretation. Thus, given the prediction that there will be no main effect for performance condition (i.e. the elevations of IMD over AMD will be nonsignificant), the hypothesis of divergence simply describes an

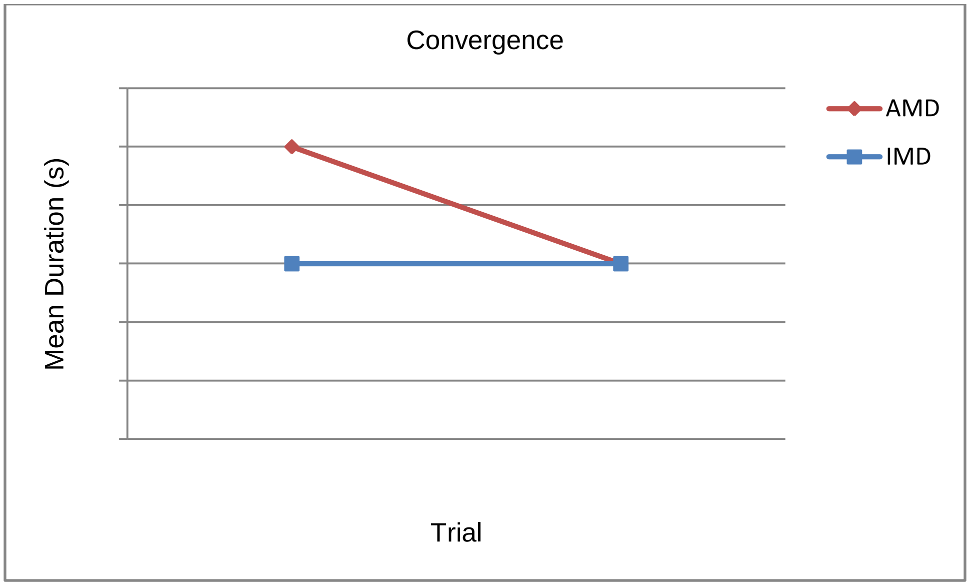

Figure 4. Convergence of actual movement duration (AMD) (red) and imagined movement duration (IMD) (blue) could possibly occur as a function of practice, resulting from a decrease in AMD and a lack of change in IMD.

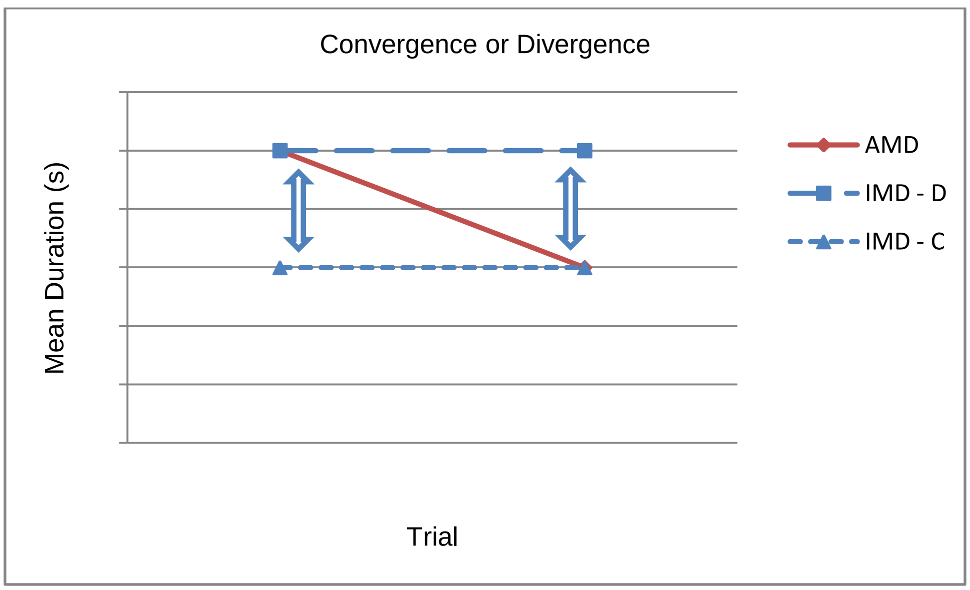

Figure 5. An expected decrease in actual movement duration (AMD) (red) can result in either convergence or divergence based on the fixed difference between AMD and IMD. If imagined movement duration (IMD – D) (blue) is longer than AMD, divergence results. If imagined movement duration (IMD – C) (blue) is shorter than AMD, convergence results.

independent decrease in AMD and a lack of change in IMD with practice and asserts nothing specific about their relationship as a function of practice. Divergence only reflects how AMD and IMD change individually with practice. In other words, the hypothesis of divergence is only concerned with how AMD and IMD change individually.

A singular decrease in AMD might imply a change in the feedback processes involved during actual action. Feedback might change with practice to adapt to the experimental task for more efficient movement. In the current experiment, arm movement is made in the sagittal plane, which has an additional torque dynamic due to gravity. With practice, it is possible that feedback components might be able to adapt and incorporate more information about the change in gravitational torque in addition to other force dynamics. Because this type of change would not affect the internal model, it would have no affect on IMDs. Since a hypothesis of divergence or convergence both describe an independent decrease in AMD and a lack of change in IMD, both possible outcomes could support this interpretation. Again, divergence is chosen over convergence as a hypothesis, because divergence is suggested by the elevations of IMD over AMD in Papaxanthis, Schieppati et al. (2002) and the results of Slifkin (2008).

If no effect for performance condition or performance condition by practice interaction is found, then the timing of actual movement is accurately predicted by the timing of imagined movement from beginning to end. This would support previous statements by Papaxanthis, Schieppati et al. (2002) that “both inertial and gravitational constraints are accurately incorporated in the timing of the motor imagery process” and support the notion that these constraints are incorporated throughout all trials.

Although differences between actual and imagined action exist, a fundamental element of emulation theory is that both share a similar internal model. To test the assumption that both actual and imagined action share a similar internal model, participants' average IMD's are correlated with their respective average AMD's to determine how much of a predictor IMD is of AMD. IMD should serve as a significant predictor of AMD if both share a common internal model.

Comparing mean duration times is only one way in which the relationship between actual and imagined movement can be studied. It is possible that online feedback contributes to the execution of movement even if average AMD and IMD do not exhibit differences. Since a participant's mean movement duration is assumed to reflect the core representation of the timing of a particular movement, the amount of deviation (i.e. variability) and how that deviation changes might reflect a process in which practice and feedback reduce timing variability for a more consistent motor representation. Having consistent timing of an action might be ideal when coordinating a sequence of actions or making adjustments in response to environmental factors. A secondary set of hypotheses tests how the variability of an individual's movement durations changes with practice and how that variability might be different between performance conditions. If no effects of practice or performance condition are found, it can be said that elements such as feedback and practice do not contribute to the temporal consistency of a motor representation. On the other hand, if an effect for performance condition or practice is found, it is possible that online feedback and practice aid the consistency of a movement's timing. Greater consistency with online feedback would be consistent with the emulation model, which suggests that emulated feedback is augmented by online feedback.

CHAPTER II

METHOD

Participants

Thirty-one (20 female), healthy, right-handed students ages 18-40 participated in the experiment. Students signed an informed consent, filled out a demographic questionnaire, and were awarded credit in a psychology course for their participation. One participant was excluded due to noncompliance with the instruction that questions and comments related to the study's hypothesis should be held until the end of the experimental session. Those who wore corrective lenses were required to wear those lenses during their experimental session.

Apparatus

Data were collected using a digital stopwatch program run on a desktop PC. A wireless mouse permitted the stopwatch software to be controlled remotely. As shown in Figure 6, a white wooden board bolted to a tripod was used as a target to guide participants' arm movements. The target board matched as much as possible to the one described for use in the vertical condition in Papaxanthis et al. (2002). Bolted to the white board were two rectangular yellow panels, one parallel to the ground, representing the horizontal position of the arm, and the other perpendicular to the floor, representing the vertical position. The widths of both the horizontal and vertical target were 14 cm. Weights consisting of metal washers were fastened by metal collars onto a wooden dowel (see Figure 7) and were used for the loaded conditions of 1 kg and 1.5 kg. Since surface texture has been found to affect weight perception (Flanagan, Wing, Allison, & Spenceley, 1995), a wooden dowel was used in the non-loaded condition to control for any effects created from the texture of the weighted dowels. The dowel also served as a control for any effects resulting from object shape and hand grip. The dowels were 33 cm in length and the washers were 5 cm in diameter. The entire experiment was conducted in a sound-attenuated chamber to prevent any distracting extraneous noise. The only light in the chamber was used to illuminate the target display. This should have had the effect of focusing participants' attention on the target display.

Figure 6. The target board consisted of two yellow targets and a white board mounted on an adjustable tripod.

Figure 7. The weights, 0 kg, 1 kg, and 1.5 kg (from left to right). The 0 kg weight consisted of a wooden dowel and the 1 kg and 1.5 kg weights consisted of metal washers attached to a dowel.

Procedure

Participants were asked to make a series of actual movements between two targets, holding different weights on different trials. On other trials, they were asked to imagine making those movements. All movements were timed.

Participants were instructed to stand to the left of the target board so that the width of their body was perpendicular to it. The experimenter then instructed the participant to extend their right arm into the "neutral position" which was perpendicular to the width of the body and parallel to the floor. At the beginning of the experimental session, the target display board was adjusted so that the participant's right shoulder was aligned with the intersection of the vertical and horizontal axes of the yellow target display panels. Ample room between their arm and the target display was left to avoid any collisions.

Next, the experimenter read the instructions on how to complete the task. On different trials, participants either actually made a series of movements or imagined making a series of movements from target to target. One trial consisted of eight movements (i.e. a cycle of four movements). The movements were to be “smooth and continuous” and made “at a pace that feels most comfortable.” A trial began with participants aligning the knuckle of their index finger within the center of the horizontal target and thus extending their arm into the neutral position. They were required to keep their arm straight and maintain a grip on the dowel in the semipronated position. When ready, they clicked a mouse resting in their left hand and commenced movement of their right arm. As the knuckle of their index finger entered the vertical target, they counted “one” silently to themselves. Then, without pausing, they smoothly reversed their movement back towards the horizontal target. When the knuckle of their index finger entered the horizontal target, they counted “two” silently. Participants then reversed the direction of their movement in the same manner until they counted “eight,” upon which they clicked the mouse a second time, simultaneous with the end of the movement cycle.

The same procedure used for the actual trials was used for the imagined trials, except participants were asked to imagine making the eight movements instead of actually performing them. Throughout their imagined movement, participants held their arm in the neutral position while gripping the load respective to the experimental condition. As mentioned, there was no arm movement during the imagined trials. Participants’ closed their eyes to form a clear and vivid mental picture of their arm and weight in their hand before they started the trial. Once imagined movement began, they were told to “vividly imagine” the movement “in as much detail as possible.”

As an initial check to make sure that the participants were imagining and performing the correct amount of movements, the experimenter took them through a couple of practice trials in which they counted aloud. The practice trials also served as a check to make sure that participants understood the instructions and clicked the mouse at the appropriate times. In addition, to reduce fatigue, participants were instructed to take a short rest between blocks if needed. A mandatory break of one minute was enforced after five blocks of trials.

Design and Analysis

Data analysis was conducted using a 2x3x10 ANOVA repeated measures on all factors. All three factors were within-participants. The first factor was performance condition (actual or imagined movement), the second was load (0 kg, 1 kg, or 1.5 kg), and the third was practice (10 successive blocks of trials). Each block of trials consisted of the six conditions created from the performance and load factors which were randomized within each block. Randomization was chosen to control for any possible order effects created by load or the interaction of load and performance condition. Randomization of the performance conditions within blocks might have introduced a confound if participants retained the memory of a previous actual trial and used this memory on a subsequent imagined trial. However, previous research has shown that the presentation order of actual and imagined trials has no effect on movement duration (Papaxanthis, Pozzo, Skoura, & Schieppati, 2002) and thus, randomization was not considered to introduce a confound into the experiment.

In light of the main hypothesis, which predicted divergence of AMD and IMD over trials, a performance condition by practice interaction was of particular interest. To learn how each performance condition may have contributed to a potential interaction, two separate planned 3x10 (load x practice) repeated-measures ANOVA’s were performed, one for each performance condition.

If actual and imagined action share a similar internal model, a participant's IMD should serve as a good predictor of their AMD. Linear regressions were calculated at each load level to determine how strong IMD served as a predictor of AMD.

An analysis of variability was also of interest to discover if online feedback or practice contribute to the consistency of a movement's timing. Variability was initially measured as the standard deviation. However, to control for any changes in mean movement duration resulting from a practice effect, residuals were used instead of raw data to calculate the standard deviation. Residuals were calculated by performing a linear regression of movement duration as a function of trials for each participant's data on each performance and load condition. After the residuals were obtained, they were grouped into blocks consisting of the first five trials and the last five trials. Standard deviations were then calculated for each block. Finally, to analyze the variability of the data, a 2x2x3 repeated-measures ANOVA (performance condition x block x load) was conducted on the resulting standard deviations.

CHAPTER III

RESULTS

A 2x3x10 repeated measures ANOVA revealed a significant effect for load ($F_{2, 60}$ = 25.441, $p < .0001$, $\eta^2 = .459$) and no significant effect for performance condition ($F_{1, 30}$ = 2.195, p = .149, $\eta^2 = .068$). These findings replicate the previous findings of Papaxanthis, Schieppati et al. (2002). Of particular interest to the current study was a significant main effect for practice ($F_{9, 270}$ = 2.897, p = .003, $\eta^2 = .088$) and a significant performance condition x practice interaction ($F_{9, 270}$ = 2.297, p = .017, $\eta^2 = .071$). The performance condition x load interaction was not significant ($F_{2,60}$ = .861, p = .428, η^2 = .028) and the load x practice interaction was not significant ($F_{18, 540}$ = .9, p = .579, η^2 = .029). The three-way interaction of performance condition x load x practice was also not significant ($F_{18, 540}$ = 1.134, p = .314, $\eta^2 = .036$).

Figure 8 displays average AMD and IMD at each load level. To follow up on the significant load effect, post-hoc pairwise comparisons were conducted on the mean durations (averaged across performance conditions) at each load level. Fisher’s LSD revealed significant differences between all of the means. The mean duration at 0 kg (8.626 s) was significantly shorter than both the mean duration at 1 kg (9.060 s) and the mean duration at 1.5 kg (9.379 s) with $p < .0001$ for both comparisons. The mean duration at 1 kg was also found to be significantly shorter than the mean duration at 1.5 kg ($p = .001$), which in the original study by Papaxanthis, Schieppati et al. (2002) was only marginally significant ($p = .062$). Not only was there a significant increase in AMD and IMD with each increased increment in load, this relationship was preserved on each trial for both AMDs and IMDs (see Figures 9 and 10).

Figure 11 displays the significant performance condition by practice interaction. Contrary to expectations, IMD was observed to be shorter than AMD on all trials, however, this main effect for performance condition was not significant. Figure 12 displays the mean difference between AMD and IMD over trials and appears to suggest convergence, however, closer examination reveals that the final difference between AMD and IMD at trial 10 ($m = .457$ s) is nearly equivalent to the initial difference at trial 1 ($m = .489$ s), suggesting little, if any, true convergence.

Although not the conservative convention given a nonsignificant performance condition x load x practice interaction, separate planned load (3) x practice (10) repeated measures ANOVA's were conducted on each performance condition. This was done to determine how each performance condition contributed to the performance condition x practice interaction. AMDs systematically reduced as a function of practice, as supported by a significant practice effect, ($F_{9, 270} = 4.677$, $p < .0001$, $\eta^2 = .135$). There was also a significant effect for load in the actual condition ($F_{2, 60} = 31.135$, $p < .0001$, $\eta^2 = .509$). There was no interaction of load by practice ($F_{18, 540} = .834$, $p = .66$, $\eta^2 = .027$).

IMDs did not change over trials as indicated by a nonsignificant practice effect ($F_{9, 270} = 1.728$, $p = .083$, $\eta^2 = .054$). It can be concluded that the decrease in AMD over trials and the lack of change in IMD over trials reflects the performance condition by

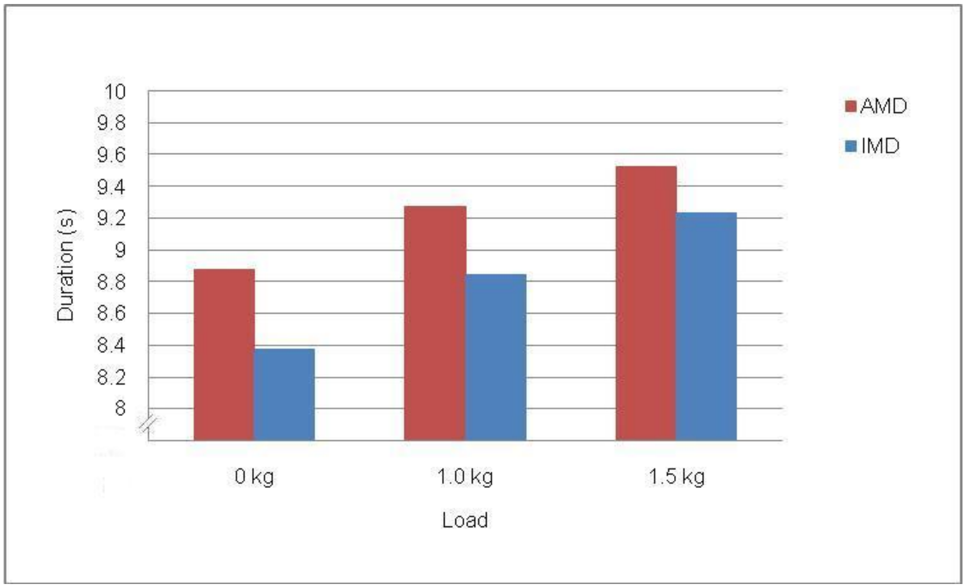

Figure 8. Mean actual movement duration (red) and mean imagined movement duration (blue) for each load condition (0 kg, 1 kg, and 1.5 kg). There is a significant increase in movement duration with each increase in load.

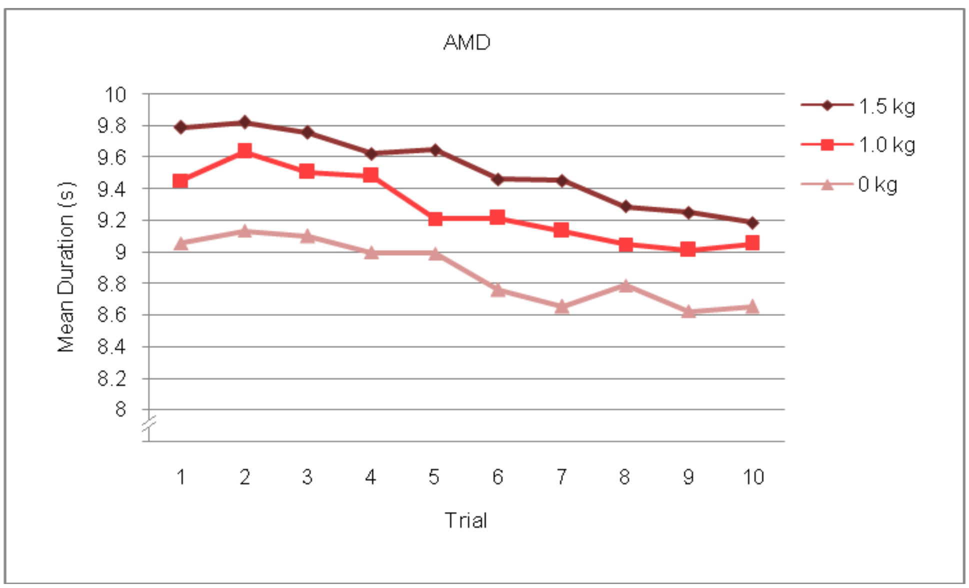

Figure 9. Mean actual movement duration (AMD) as a function of practice for each load condition (0 kg, 1 kg, and 1.5 kg) (light, medium, and dark red, respectively).

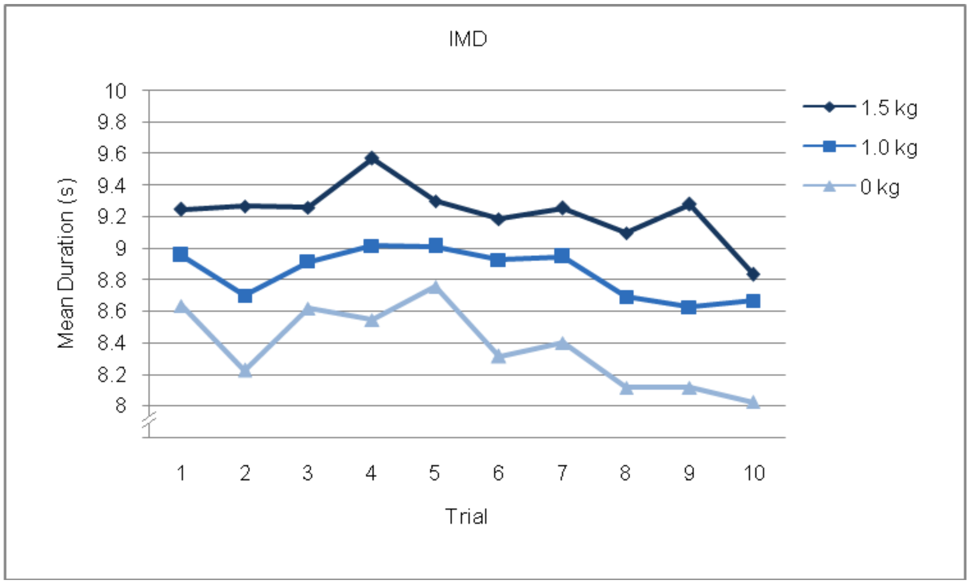

Figure 10. Mean imagined movement duration (IMD) as a function of practice for each load condition (0 kg, 1 kg, and 1.5 kg) (light, medium, and dark blue, respectively).

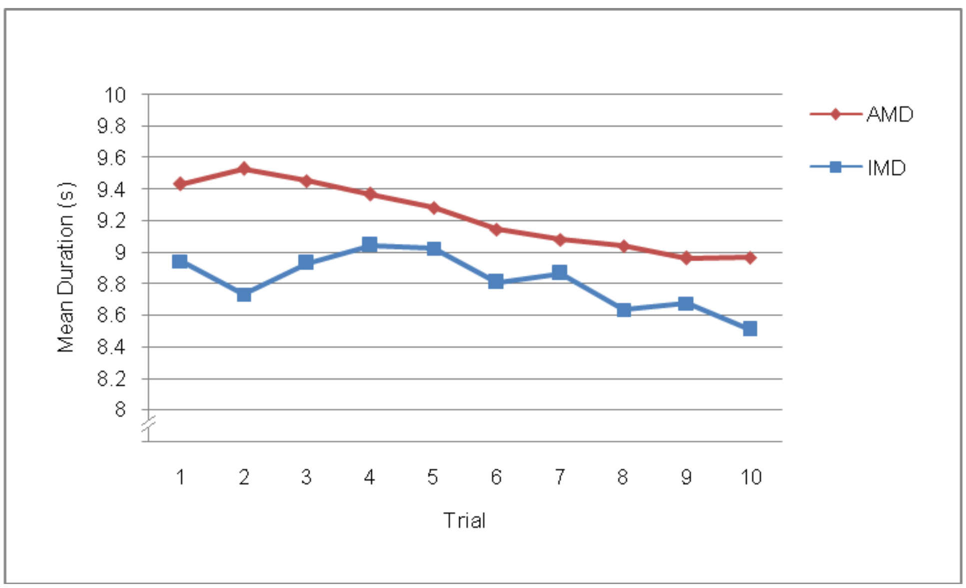

Figure 11. Mean actual movement duration (AMD) (red) and mean imagined movement duration (IMD) (blue) as a function of practice. There is a significant decrease in AMD as a function of practice and no significant change in IMD.

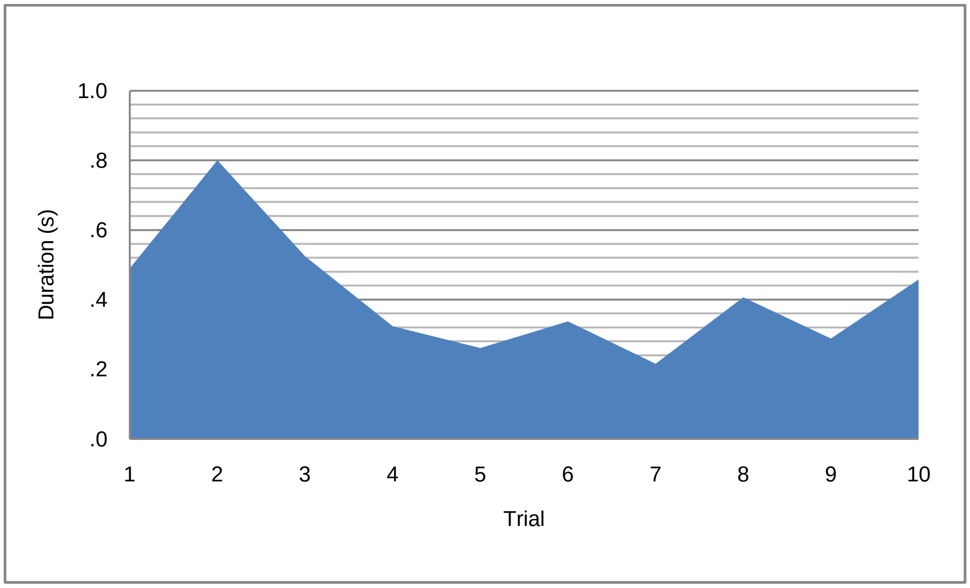

Figure 12. The mean difference between actual and imagined movement duration as a function of practice. The difference at trial one is similar to the difference at trial ten.

practice interaction in the overall ANOVA (see Figure 11). A significant effect for load in the imagined condition ($F_{2, 60} = 13.160$, $p < .0001$, $\eta^2 = .305$) indicates that the main effect for load in the overall ANOVA was not solely carried by the actual condition. Like the actual condition, there was no interaction of load and practice ($F_{18, 540} = .834$, $p = 1.083$, $\eta^2 = .035$)

To test how good of a predictor a participant's IMD was of their AMD, linear regressions were performed at each load level. Figure 13 displays the linear regressions for the 0 kg, 1 kg, and 1.5 kg conditions. Each point represents a single participant's AMD and IMD for a respective load condition. At 0 kg, the correlation between AMD and IMD was significant ($r = .843$, $p < .0001$). The correlation at 1 kg was also significant ($r = .769$, $p < .001$) as well as the correlation at 1.5 kg ($r = .733$, $p < .0001$). Because the r values were high, a participant's IMD appears to be a strong predictor of

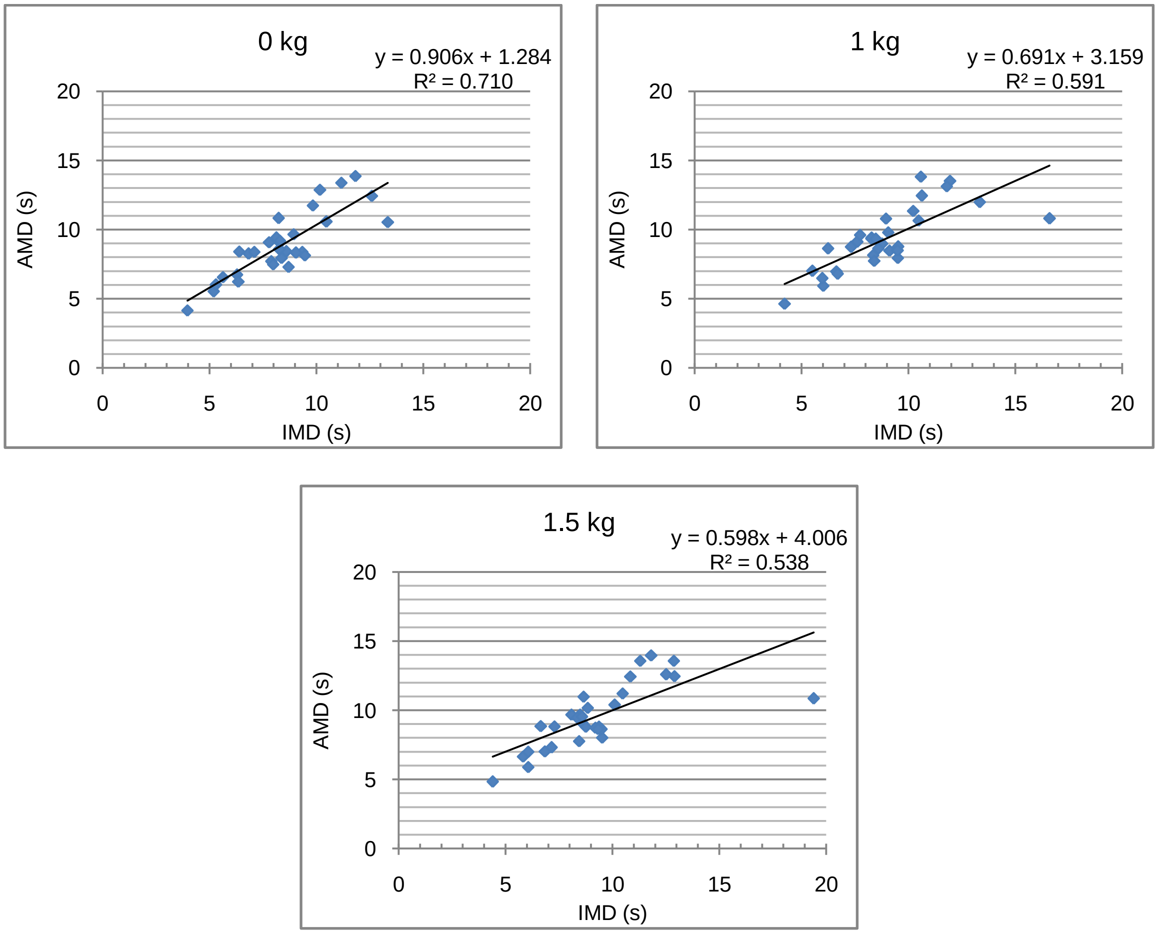

Figure 13. Linear regressions of actual movement duration (AMD) as a function of imagined movement duration (IMD) at each load level (0 kg, 1 kg, and 1.5 kg). Each point represents a participant's AMD and IMD for a particular load condition. A fanning out of points from the regression line can be observed for longer movement durations.

their AMD and therefore an internal model seems to be the underlying factor accounting for the shared variance between the two variables. Looking closely at the graphs, a spread or fanning out from the regression line can be observed for longer AMDs and IMDs. If we assume that the ratio of IMD to AMD in a single participant is an effect separate from the overall movement duration, then it becomes clear that a ratio of say, 4:5 would produce a 1 s difference given an IMD of 4 s. If IMD were 8 s, then the difference would increase to 2 s. In this way, longer times have the potential to result in larger differences.

The averages of the standard deviations of AMD and IMD for the first and second block of trials appear in Figure 14. A 2x2x3 repeated-measures ANOVA (performance x block x load) revealed a significant main effect for performance condition ($F_{1, 30}$ = 28.137, $p < .0001$, $\eta^2 = .484$), showing that variability was larger for the imagined condition (M = .631 s) than the actual condition (M = .404), a finding similar to previous studies that have shown that the distribution of imagined durations to be larger than that of actual durations (Papaxanthis, Pozzo et al., 2002). This suggests that the availability of online feedback in the actual condition aids the consistency of a movement's timing. In other words, feedback might facilitate consistent timing by providing more information about movement dynamics to the CNS. Since feedback is only available in the actual condition, this difference in variability between the two performance conditions can be attributed to this source of feedback. There was also a main effect for block ($F_{1, 30}$ = 28.433, $p < .0001$, $\eta^2 = .487$) showing that variability decreased for both performance conditions from the first block (M = .598) to the last block (M = .437). This similar change in consistency as a result of practice suggests that a common underlying process is undergoing change in a similar way. Since both types of movement share a common internal model, a similar decrease in variability for both types of movement indicates a change involving the internal model.

There was no significant effect for load ($F_{2, 60}$ = .328 $p = .722$, $\eta^2 = .487$), however, there was a near significant effect for a load by block interaction ($F_{2, 60}$ = 2.995, $p = .058$, $\eta^2 = .091$). There is a tendency toward greater decreases in variability with

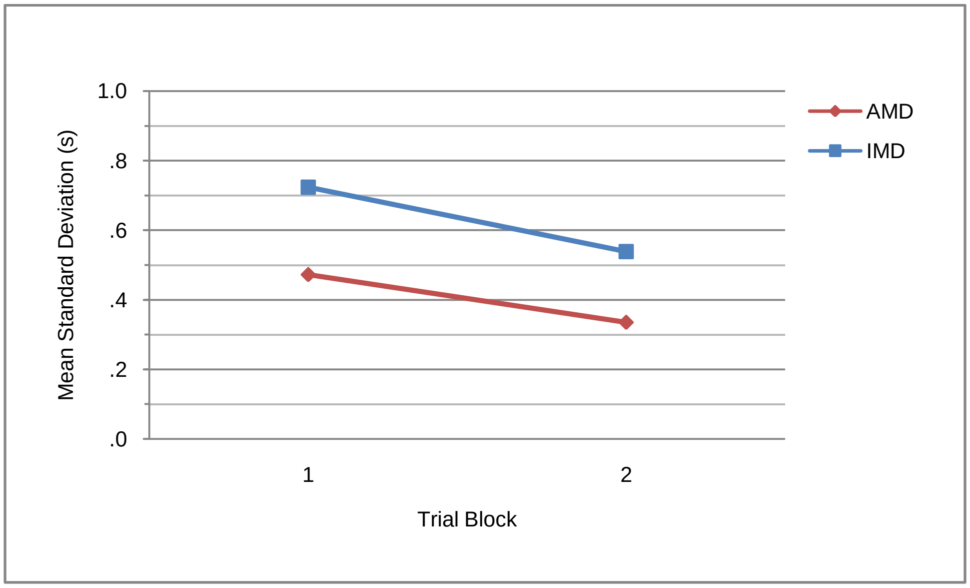

Figure 14. Variability measured as the mean standard deviation of actual movement duration (red) and the mean standard deviation of imagined movement duration (blue) as a function of practice. Variability decreases significantly with practice from Trial Block 1 to Trial Block 2. Variability of AMD is significantly less than the variability of IMD.

increases in load. It is possible that this tendency is the result of a floor effect, meaning that the variability of movement duration cannot decrease much past the point at which the non-loaded condition began. The details of this will be saved for the discussion. The interaction of performance condition and load was nonsignificant ($F_{2, 60}$ = .362 p = .698, η^2 = .012). The interaction of performance condition and practice was also nonsignificant ($F_{1, 30}$ = .786 p = .698, η^2 = .026).

CHAPTER IV

DISCUSSION

AMD vs. IMD

The purpose of the current study was to examine actual and imagined movement duration under conditions of practice and added load under the basic framework of emulation theory. The study by Papaxanthis, Schieppati et al. (2002) provided a basis to further explore how AMD and IMD evolved over trials. Like that study, the current study found a significant main effect for load as well as a nonsignificant effect for performance condition. The replication of the main effects from Papaxanthis et al. provides further validity to the current analyses of practice effects.

The original hypothesis predicted that AMD and IMD would diverge as a result of a significant decrease in AMD and a lack of change in IMD. The current results also show a significant decrease in AMD and a lack of change in IMD, however, since AMD was longer than IMD, the decrease in AMD appears to result in convergence. This does not pose a problem for an interpretation of the results since the fixed difference between AMD and IMD (which dictated convergence or divergence) was found to be nonsignificant. Thus, the independent change in AMD and the lack of change in IMD is the result of interest. It is worth noting that the difference between AMD and IMD at trial block one is nearly equivalent to the difference at trial block ten, suggesting little, if any convergence, and further supporting the notion that the reduction in AMD and lack of change in IMD is the result of interest. This result is also corroborated by Slifkin (2008). Recall that in that study, IMD was initially longer than AMD and the significant decrease in AMD and the lack of change in IMD resulted in an apparent divergence. From the Slifkin study and the current study, it seems clear that with practice, AMD decreases and IMD is resistant to change.

Since IMD is resistant to change, it suggests that the internal model is resistant to change. The internal model's resistance to change might reflect a process in which catastrophic interference of previous motor learning is prevented. Catastrophic interference causes previously learned information to be quickly lost upon the introduction of new information. This effect has been observed in computer simulations of connectionist models (McCloskey & Cohen, 1989) and poses a problem to theories of learning, problems that the human brain has mostly solved. In general, catastrophic interference does not occur in human motor memory. Learning to ride a bicycle will not affect a person's ability to walk. However, catastrophic interference has been documented when the skill lost was learned within a short time prior to learning the interfering skill (Brashers-Krug, Shadmehr, & Todorov, 1995). In the study by Brashers-Krug et al., learning movement in one force field was lost because of subsequent learning in a new force field. Later research using similar methodology suggested that motor learning must undergo a period of consolidation (5 h) before it is no longer susceptible to the catastrophic interference of subsequent learning (Shadmehr & Brashers-Krug, 1997). In light of the current study, it is possible that IMDs reflect past consolidated learning and that AMDs reflect new changes that are still in a labile state. This explanation would predict that if opposing force dynamics were introduced and practiced right after the current task, it would interfere with the new learning, evidenced by a change in AMD but no change in IMD. In the absence of an interfering task, it would be expected that IMDs would change only after the consolidation period.

Details of the results from Shadmehr & Brashers-Krug (1997) appear to challenge the notion that the internal model only undergoes change after the consolidation period. While learning an interfering force field, participants showed aftereffects from learning a prior force field much before the end of the consolidation period. These aftereffects were recorded 300 ms into the movement. Corrections from feedback are typically only available after about 200 ms, the amount of time to complete the sensorimotor loop that spans from the involved limb to the cerebral cortex. In other words, corrections made before 200 ms reflect predictions made by an internal model. The aftereffects recorded at 300 ms suggest that changes in the feedback process from the peripheral nervous system did not play the entire role in learning the first force field. It appears that an internal model of the first force field was present well before the end of the consolidation period. This seems to be problematic if we assert that IMDs represent the internal model but do not represent new adaptations.

Consistent with the findings of Shadmehr & Brashers-Krug (1997), it is possible that the feedback system does play a more prominent role in the initial acquisition of a motor skill if we include structures from the CNS as components of the feedback system that would be active before and after the 200 ms window. The cerebellum has been implicated in the coordination of feedback, and is found to be relatively inactive during motor imagery when compared to actual movement (Lotze, Montoya, Erb, Hulsmann, Flor et al., 1999; Nair, Purcott, Fuchs, Steinberg, & Kelso, 2003). It is possible that before consolidation, adaptive changes are mostly present in the cerebellum and are less accessible to imagery. In fact, patients with cerebellar degeneration show deficits in predictive learning when compared to controls suggesting that the cerebellum plays a key role in the initial acquisition of a motor skill (Smith & Shadmehr, 2005). This does not imply that the entire motor representation is stored in the cerebellum until consolidation, but suggests that before consolidation, the cerebellum makes important supplemental changes to the afferent and efferent motor signal as a result of learning. In the current study, the decrease in AMD and lack of change in IMD is suggestive of changes made to the cerebellum, changes less accessible to imagery.

The finding that AMD decreased with practice and IMD resisted change appears to be in conflict with some of the results from previous research (Papaxanthis, Schieppati et al., 2002; Gentili, Cahouet, Ballay, & Papaxanthis, 2004). It is possible that Papaxanthis, Schieppati et al. did not report any practice effects because their design did not permit such an analysis. Like the current study, trials were randomly presented, however, their trials were presented in blocks of 20 (10 actual and 10 imagined), and therefore did not allow for each block to have a balanced number of load conditions. A balanced number of conditions would be dividable by six, the number of unique conditions created from the three loads and two performance conditions. Even if the blocks were balanced, durations from the same condition would have to be averaged so that only three blocks could be considered in an analysis of practice effects. The current study took the experimental design a step further by creating 10 balanced blocks, therefore allowing a proper analysis of the practice effects.

Results of a similar experiment examining arm movement (Gentili, Cahouet, Ballay, & Papaxanthis, 2004) contrast with the current finding that AMD decreased and IMD remained the same with practice. Gentili et al. stated, “It can be noted that variations in duration from one trial to the next were small for both overt [actual] and covert [imagined] movements” (p. 235). It is possible that changes as a function of practice were not found in Gentili et al. (2004) because arm movement was completed in the horizontal plane. Movement directed in the horizontal plane is much simpler than movement directed in the sagittal plane. Later research by Gentili, Cahouet, & Papaxanthis (2007) suggested that motor plans are direction-dependent, citing that movement in the sagittal plane has an additional dynamic of gravitational torque which changes as a function of movement. These changes in torque require a more complex motor plan. In Gentili et al., AMD showed little change as a function of practice. In the current study, AMD might have decreased because the added complexity in the sagittal plane permitted a greater potential for change. In other words, a less complex movement would likely benefit less from practice because those dynamics are easier to internalize, and therefore near optimal movement duration would be present from the start.

Correlation of AMD and IMD

Significant correlations between IMD and AMD further support the notion that IMD reflects the internal emulation model utilized by actual performance. The fanning out observed for longer AMDs and IMDs suggest that the ratio of AMD to IMD is an effect separate from overall length of duration. If such an effect exists, the nonsignificant difference between AMD and IMD might be better understood. A separate effect would imply that longer overall durations are contributing to an apparent difference more than shorter overall durations. This might be an area of interest for future research that attempts to understand the relationship between actual and imagined action.

Variability of Movement Durations

The formation of a motor representation can be considered a process in which the brain attempts to represent the ideal of an action or how the action will be executed. The consistency of the timing of an action is a reflection of the degree to which the brain has knowledge of the outcome. If the output distribution of duration times is wide, then less is known about the outcome of the action. If the distribution is narrow, then the timing of the action can be executed with greater consistency, and thus there is less uncertainty in predicting the outcome.

The significant difference between the variability of AMD and IMD provides further support to the components of the emulation model. Indeed, if both emulation and live feedback are present in the actual condition, it is parsimonious that this greater consistency is due to the availability of feedback. The variability of both performance types also decreased with practice, suggesting a change in how the internal model is executed. Because this seems to contradict the interpretation that the internal model is resistant to change, further explanation is required.

There is a difference between changing how consistent the outcome will be and changing the outcome. When mean AMD decreases with practice, this is a change in the outcome or how the movement is controlled. When variability of both AMD and IMD decreases, this is a change in the consistency of the outcome or how consistent the internal model is executed. Neither type of change requires the other. So why might the internal model not be resistant to an increase in consistency? An increase in the internal model's consistency would not require protection since the internal model already reflects protected and consolidated learning unaffected by recent learning. This implies that the internal model has a self-correcting mechanism for consistency that is not dependent upon live feedback. This assertion is not entirely unreasonable given that information to execute the intended action is already encoded. Although this information might not be optimal, it is sufficient to complete the action and can benefit from improvements in consistency. Greater consistency allows greater predictability of the outcome, and thus might afford more efficient planning of a series of movements.

This increase in consistency with practice was found to be marginally higher with added load. It is possible that movement consistency at higher loads benefitted more from practice because participants have less experience with loaded movement in the sagittal plane. This lack of experience might have created a greater potential for improvement in the added load conditions.

Conclusion

It is apparent that practice does have an effect on actual and imagined movement as supported by a performance condition by practice interaction. The change in AMD and lack of change in IMD with practice suggests that IMD might reflect learning protected from catastrophic interference and therefore IMD might only change after a period of consolidation. It is possible that changes in AMD with practice reflect adaptations made mainly in the cerebellum, a structure less accessible to imagery. When examining the variability of AMDs and IMDs, there was a main effect for practice and for performance condition. It appears that both practice and the availability of feedback contribute to the consistency of a movement's timing. All of these findings in addition to the significant correlations between AMD and IMD support the notion that actual and imagined movement share a similar internal model but do not share the feedback process exclusive to actual movement. Future research in motor imagery might employ a more controlled environment such as a velocity or acceleration dependent force field to more fully understand the role of imagery in human motor learning. By gaining a detailed understanding of the motor imagery process and learning, it is the hope of the author that motor imagery will be better used by professionals as a technique to rehabilitate a motor deficit or teach a motor skill.

REFERENCE

Brashers-Krug, T., Shadmehr, R., & Todorov, E. (1995). Catastrophic interference in human motor learning. In G. Tesauro, D. Touretzky, & T. Leen (Eds.), *Advances in neural information processing systems*, (Vol. 7, pp. 19–26). Cambridge, MA: MIT.

Calmels, C., Holmes, P., Lopez, E., & Naman, V. (2006). Chronometric Comparison of Actual and Imagined Complex Movement Patterns. *Journal of Motor Behavior, 38*, 339-348.

Cerritelli, B., Maruff, P., Wilson P., & Currie, J. (2000). The effect of an external load on the force and timing components of mentally represented actions. *Behavioural Brain Research*, 108, 91-96.

Crossman, E. (1959). A theory of the acquisition of speed skill. *Ergonomics, 2*, 153-166.

Decety, J., & Michel, F. (1989). Comparative analysis of actual and mental movement times in two graphic tasks. *Brain and Cognition, 11*, 87-97.

Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. *Behavioural Brain Research, 34*, 35-42.

Dechent, P., Merboldt, K., & Frahm, J. (2004). Is the human primary motor cortex involved in motor imagery?. *Cognitive Brain Research, 19*, 138-144.

Desmurget, M., & Grafton, S. (2000). Forward Modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*, 423-431.

Flanagan, J., Wing, A., Allison, S., & Spenceley, A. (1995). Effects of surface texture on weight perception when lifting objects with a precision grip. *Perception & Psychophysics, 57*, 282-290.

Gentili, R., Cahouet, V., Ballay, Y., & Papaxanthis, C. (2004). Inertial properties of the arm are accurately predicted during motor imagery. *Behavioural Brain Research, 155,* 231-239.

Gentili, R., Cahouet, V., & Papaxanthis, C. (2007). Motor planning of arm movements is direction-dependent in the gravity field. *Neuroscience, 145,* 20-32.

Grush, R. (2004). The emulation theory of representation: motor control, imagery, and perception. *Behavioral and Brain Sciences, 27,* 377-396.

Lotze, M., Montoya, P., Erb, M., Hulsmann, E., Flor, H., Klose, U., Birbaumer, N., & Grodd, W. (1999). Activation of cortical and cerebellar motor areas during executed and imagined hand movements: an fMRI study. *Journal of Cognitive Neuroscience*, *11,* 491-501.

McCloskey, M., & Cohen, N. (1989). Catastrophic interference in connectionist networks: The sequential learning problem. In G. H. Bower (Ed.), *The psychology of learning and motivation*, (Vol. 24, pp. 109–165). New York: Academic Press.

Nair, D., Purcott, K., Fuchs, A., Steinberg, S., & Kelso, J. (2003). Cortical and cerebellar activity of the human brain during imagined and executed unimanual and bimanual action sequences: a functional MRI study. *Cognitive Brain Research, 15,* 250-260.

Orliaguet, J., & Coello, Y. (1998). Differences between actual and imagined putting movements in golf: a chronometric analysis. *International Journal of Sport Psychology, 29,* 157-169.

Papaxanthis, C., Pozzo, T., Skoura, X., & Schieppati, M. (2002). Does order and timing of imagined and actual movements affect the motor imagery process? The duration of walking and writing task. *Behavioural Brain Research, 134,* 209-215.

Papaxanthis, C., Schieppati, M., Gentili, R., & Pozzo, T. (2002). Imagined and actual arm movements have similar durations when performed under different conditions of direction and mass. *Experimental Brain Research, 143,* 447-452.

Porro, C., Francescato, M., Cettolo, V., Diamond, M., Baraldi, P., Zuiani, C., Bazzocchi, M., & Prampero, P. (1996). Primary motor and sensory cortex activation during motor performance and motor imagery: A functional magnetic resonance study. *The Journal of Neuroscience, 16,* 7688-7698.

Reed, C. (2002). Chronometric comparisons of imagery to action: Visualizing versus physically performing springboard dives. *Memory & Cognition, 30,* 1169-1178.

Roth, M., Decety, J., Raybaudi, M., Massarelli, R., Delon-Martin, C., Segebarth, C., Morand, S., Gemignani, A.,Decorps, M., & Jeannerod, M. (1996). Possible involvement of primary motor cortex in mentally simulated movement: a functional magnetic resonance imaging study. *NeuroReport, 7,* 1280-1284.

Shadmehr, R., & Brashers-Krug, T. (1997). Functional stages in the formation of human long-term motor memory. *Journal of Neuroscience, 17,* 409-419.

Smith, M., & Shadmehr, M. (2005). Intact ability to learn internal models of arm dynamics in Huntington's disease but not cerebellar degeneration. *Journal of Neurophysiology, 93,* 2809-2821.

Slifkin, A. (2008). High loads induce differences between actual and imagined movement differences. *Experimental Brain Research, 185,* 297-30.

Wolpert, D., Ghahramani, Z., & Jordan, M. (1995). An internal model for sensorimotor integration. *Science*, *269*, 1880-1882.