

ABSTRACT

Title of Document:

PSYCHOPHYSIOLOGICAL INVESTIGATION OF ATTENTIONAL PROCESSES DURING MOTOR LEARNING

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As one becomes more proficient at a motor task the attentional demand required to perform that task decreases. Behavioral evidence suggests that experienced individuals possess greater attentional reserve during task execution compared to novices, such that, they are better able to cope with additional, possibly unexpected, challenges. This advantage may be the result of streamlining the neural processes underlying motor planning and execution over the course of learning. Such psychomotor efficiency reduces the demand on cortical resources imposed by the primary task such that they are available for coping with challenge beyond that of the task. However, this hypothesis has not been tested. The aim of this study was to provide neurobiological evidence of the positive relationship between motor skill and attentional reserve.

Twenty-one participants were randomly assigned to one of two groups, a group that learned a novel visuomotor distortion task, and a control group that

performed the same task with no distortion (i.e., no learning). For the duration of the task, event-related brain potentials (ERPs) elicited by a set of novel stimuli were recorded. The dynamic modulation of ERP component amplitude was used as an index of attentional reserve. We predicted that component amplitudes would initially be diminished in the learning group relative to the control group, but that there would be a progressive increase in amplitude as a function of learning; by contrast, we predicted that ERP component amplitudes would remain relatively stable in the control group.

Importantly, task performance, as measured by initial directional error, was initially worse in the learning group relative to control group and significantly improved over the course of exposure, whereas the control group's performance was stable. This suggests the visuomotor distortion task employed was successful in serving as a model of motor skill acquisition. Analyses of the ERPs elicited by the auditory probes revealed that the exogenous components, N1 and P2, were not different between the two groups and did not change over the course of learning suggesting that early sensory processing was comparable between the two groups. Notably, the novelty P3 component—an index of the involuntary orienting of attention--was initially attenuated in the learning group relative to the control group, but progressively increased in amplitude as a function of learning in the learning group only. This suggests that attentional reserve increased as a function of motor skill acquisition, such that greater attentional resources were available to process the auditory probes.

The current study provides psychophysiological evidence that attentional reserve increases as a function of motor skill acquisition. Moreover, the metric developed for this study provides a means to assess cognitive/motor learning in both applied cognitive and clinical domains.

PSYCHOPHYSIOLOGICAL INVESTIGATION OF ATTENTIONAL
PROCESSES DURING MOTOR LEARNING

By

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Study 2

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Note: for a given trial only one target will be displayed at a time.

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Overview

My graduate work has largely focused on the neural underpinning of superior performance, specifically investigating the brain processes which underlie one's ability to perform at their best, and conversely can contribute to their worst performances. My program of study has examined the impact of factors such as motor learning, expertise, stress, task difficulty and even individual differences (personality characteristics and genetic variants) on the cerebral- cortical dynamics associated with cognitive-motor challenge. More recently, I have become interested in the how cognitive workload influences performance and, accordingly, how the brain's management of workload may be affected by the aforementioned factors as well. An integral aspect of cognitive workload is how attentional resources are directed and to what magnitude. In this regard, I have conducted three experiments, which programmatically explore the neurobiology of attentional processes and their relationship to the many facets of cognitive-motor performance. They are presented in this document with the third study being the dissertation work.

Task difficulty would likely impact attentional processes, such that greater difficulty would both increase cognitive workload and consume attentional resources. Thus it was important to demonstrate that changes in task difficulty would elicit alterations in cortical dynamics known to be consistent with increased cognitive workload. In accord, the first study was designed to determine the impact of difficulty on cerebral-cortical dynamics during a cognitive-motor task (study manuscript submitted for publication to the journal *Biological*

Psychology). The extant superior performance literature has largely focused on cognitive workload using expert-novice contrasts. From this body of work, a principle referred to as psychomotor efficiency has emerged. The central tenet of this principle states that as expertise is acquired the neural processes associated with the relevant skill become more refined. This streamlining of ‘neural effort’ is thought to include both a reduction in task-irrelevant processing and attenuated networking to brain regions known to be involved in motor planning. To test if psychomotor efficiency underlies superior performance beyond that of expert versus novices, I manipulated the speed of a cognitive-motor video game to determine if harder conditions would be characterized by reduced efficiency. This notion was supported, please see Study 1. Harder conditions did elicit a reduction in psychomotor efficiency (i.e. greater cognitive workload), as indexed by increased EEG coherence to motor planning areas along with regionally and bandwidth specific increases in cortical activation. The next step was to determine how this reduction in psychomotor efficiency impacts attentional processes.

In an effort to index attentional resources, I developed a novel metric by probing individuals with a variety of novel, task-irrelevant, auditory stimuli during a cognitive-motor challenge while acquiring 64-channels of EEG. I predicted that with increases in task difficulty (varied speed of processing during a challenging video game) more attention would be consumed leaving fewer resources available to process the sounds. Audio evoked potentials were derived and the amplitude of the novelty P3 component was used to index the compulsory orienting of attention during different levels of difficulty (please see Study 2. This

study manuscript was accepted for publication by the *International Journal of Psychophysiology*). As expected there was an inverse relationship between novelty P3 amplitude and task-difficulty, which behaved in a dose-dependent manner. This suggest two things, 1—that this is a viable metric for indexing attentional reserve during cognitive-motor challenge, and 2—increases in task difficulty impose greater demands on attention.

To further this psychophysiology-based program of study and better understand the extent to which this metric (developed in Study 2) would generalize, my dissertation employed a motor-learning based strategy. I hypothesized that as cognitive-motor learning progressed, attentional resources would become available. This ‘freeing up’ of attentional resources would be reflected by increased amplitudes of the novelty P3 component (decreased task demand) providing psychophysiological evidence that attentional reserve increases as a function of motor skill acquisition. For results please see Study 3, the work specific to the dissertation.

Study 1

Cerebral-cortical networking and activation increase as a function of cognitive-
motor task difficulty

Abstract

Excessive increases in task difficulty typically result in marked attenuation of cognitive-motor performance. The psychomotor efficiency hypothesis suggests that poor performance is mediated by non-essential neural activity and cerebral cortical networking (inefficient cortical dynamics). This phenomenon may underlie the inverse relationship between excessive task difficulty and performance. However, systematic investigation of the psychomotor efficiency hypothesis, as it relates to task difficulty, has not been conducted. The present study used electroencephalography (EEG) to examine cerebral cortical dynamics while participants were challenged with both Easy and Hard conditions during a cognitive-motor task (Tetris®). In accord with the psychomotor efficiency hypothesis, it was predicted that participants would demonstrate higher levels of neural activity, as measured by spectral power, and cortical networking (i.e., coherence) between the premotor (motor planning) region and sensory, executive, and motor regions concomitant with decreased task performance in the Hard condition relative to the Easy. Increases in neural activation and cortical networking were observed in conjunction with decreased task performance during the Hard condition relative to the Easy condition, thus supporting the psychomotor efficiency hypothesis. Crucially, the present study is the first, to our knowledge, to report changes in cortical networking due to modulations of cognitive-motor task difficulty. The present study's findings further inform the dynamics of the cortical processes that may underlie the quality of cognitive-motor performance. A broader understanding of the brain and muscle interactions

during varying levels of challenge may inform the design of effective training protocols aimed at optimizing cognitive-motor performance.

Introduction

Excessive increases in task difficulty typically compromise performance. The psychomotor efficiency hypothesis suggests that superior performance is resultant of economic neural activation in motor regions and efficient networking between motor and non-motor regions. On the other hand, poor performance is mediated by non-essential levels of neural activity resulting in inefficient cerebral cortical dynamics. Moreover, non-essential cortical activity may impair motor output by disrupting the recruitment of first order motor neurons and hinder sensory input via maladaptive attentional resource allocation (Hatfield & Hillman, 2001; Hatfield & Kerick, 2007). This phenomenon may underlie the relationship between cognitive-motor task difficulty and performance. However, the nature of this relationship has not been well characterized. Understanding this relationship may yield insights into costly performance failures as well as drive strategies aimed at enhancing performance under a wide range of task difficulties. A number of studies have employed electroencephalography (EEG) to determine the impact of task difficulty on cerebral-cortical dynamics. However, these studies have constrained their analyses to the examination of isolated cortical activation in a limited number of cortical regions (see Gevins & Smith, 2008). To better characterize the task difficulty-cortical dynamics relationship, the present study examined both cortical activation (spectral power) and cerebral-cortical networking (coherence) at multiple frequency bandwidths across the scalp topography.

Spectral power analyses provide an index of the degree of synchronous neural activity within a frequency bandwidth of interest (greater synchrony results in greater power). Different psychological processes have been characterized by both regionally and bandwidth-specific neural activity. Previous studies have examined the impact of task difficulty on spectral power through analyses of electrode sites overlying task-relevant regions of the cortex. Specifically, prior work has examined frontal lobe theta synchrony, which indexes attentional engagement, and revealed a positive relationship between task difficulty and theta synchrony. Previous research has also examined parietal alpha desynchrony, which indexes multimodal sensory integration, and observed a positive relationship between task difficulty and alpha desynchrony. In both the frontal theta and parietal alpha analyses, increases in task difficulty were accompanied by decreases in performance (see Gevins & Smith, 2008).

While the majority of these spectral power-task difficulty studies have used purely cognitive tasks (e.g., N-back), similar findings have also been reported in studies employing cognitive-motor challenges. Sauseng et al. (2007) reported frontal theta synchrony as the difficulty of a complex finger movement task was increased. Similarly, Mizuki et al. (1982) reported frontal theta synchronization during the more difficult stages of a simulated driving task. Further, Serman and Mann (1995) reported increased parietal alpha desynchronization with increased difficulty in a flight simulation task. As these studies reveal a positive relationship between task difficulty (task demand) and

cortical activation (neural effort) along with concomitant performance decrements they are consistent with the predictions of the psychomotor efficiency hypothesis.

While these spectral power studies have been useful in understanding the neural underpinnings mediating cognitive-motor task difficulty and performance, they focus on isolated regionally-specific cortical activation as opposed to global cerebral-cortical networking. From a cognitive neuroscience perspective, it is largely agreed upon that the brain operates through disperse interconnected regions (i.e., networks) (see Laughlin & Sejnowski, 2003; Sporns, Tonini, Kötter, 2005). Thus, examination of cortical networking could further inform the cognitive-motor task difficulty-performance relationship. Specifically, the metric EEG coherence, a statistical measure of the degree of repeated linear correlation of the spectral power in a specified bandwidth between two separate electrodes, provides an index of cortical networking. High coherence implies a large degree of cortico-cortical communication between different brain regions whereas low coherence posits relative independence.

As networking is a key component of cortical dynamics, it is surprising that there have been few reports of changes in EEG coherence due to changes in cognitive-motor task difficulty. However, differences in cortical networking between expert performers and those with less skill have been reported for cognitive-motor tasks. For example, Deeny, Hillman, Janelle, and Hatfield (2003) reported that expert marksmen exhibited less networking between cognitive and motor regions during the aiming period of a rifle shooting task relative to less skilled marksmen. In addition, networking has been demonstrated to change as a

function of learning a cognitive-motor task. For example, Bell and Fox (1996) studied networking in infants learning to crawl and observed that, with gains in crawling experience, networking was reduced. Additionally, Busk and Gailbrith (1975) observed that practicing a cognitive-motor task in a performance-enhancing manner led to decreases in networking. In summary, these studies examining networking as a function of skill level/learning illustrate that enhanced performance in experts compared to those with less skill and throughout learning are associated with refinements in cortical networking (EEG coherence). Given that task mastery is associated with refined networking, as illustrated by the aforementioned studies, it follows that excessive increases in cognitive-motor task difficulty may lead to less-refined cortical networking as indexed by increases in EEG coherence due to the disruption of task mastery.

In accord with this notion, it was hypothesized that task difficulty will be positively related to cortical networking. To test this hypothesis task difficulty while holding expertise constant to control for the influence of motor learning during a cognitive visuomotor challenge (playing the game Tetris®). Tetris® is a videogame that requires players to manipulate different-shaped game pieces in order to place them in their optimal location on the game board (computer screen). While a player is manipulating a piece, the subsequent piece is displayed on the screen so that the player may better optimize the current piece's placement with consideration of the next piece. Given the inherent cognitive-motor challenge of playing Tetris® and consistent with the psychomotor efficiency hypothesis, it was predicted increased coherence between the premotor (motor

planning) area and distributed motor, sensory, and executive regions during the more difficult task condition. Additionally, while previous work examining changes in spectral power (cortical activation) due to variations in task difficulty has largely limited its reported findings to frontal theta synchrony and parietal alpha desynchrony, the present study considers multiple bandwidths and across the scalp topography. However, given the extant literature cited above, frontal theta synchrony and parietal upper alpha desynchrony during the more difficult condition compared to the less difficult was predicted.

Materials and Methods

These data were collected as part of a larger effort and the materials and methods presented here reflect only those procedures relevant for the present analysis. The comprehensive methodology is described in Miller, Rietschel, McDonald, and Hatfield (2011).

Participants.

Twelve men and 11 women were recruited from a large metropolitan area. The data from three of the participants were removed due to poor electrophysiological recordings, so the final sample contained 20 individuals (10 women, with a mean age of 24.4(4.1) ranged 20-33 years). Tetris® playing experience varied from never having previously played to having played more than 50 hours. All participants provided informed written consent.

Procedures.

Participants sat in front of a 15" computer monitor and used a computer keyboard to play Tetris® while the song "Korobeiniki" ("Music A" in the standard Tetris® game) was played (72 - 76 dB SPL) from a speaker next to the monitor. Participants engaged in one easy condition of Tetris® and one hard condition. Each condition lasted approximately 8 min. During the Easy condition, participants began play at level 1. During the Hard condition, participants began play at level 8. After completing a level (i.e., completing 10 lines of pieces), participants immediately advanced to the next level of the game. For each successive level, the game became more challenging due to an increased rate of

speed with which the pieces fell. At level 1, the pieces fell at a velocity of 1.67 cm/s, while at level 8 they fell at a velocity of 3.56 cm/s. Although the game allows the player to manually increase the speed at which the pieces fall, speed was held constant within a level as the participants were instructed not to manually advance the pieces. The change in speed was believed to impact upon task difficulty as the participants had to more rapidly determine where to place the current piece, execute the placement, and update their planning for the successive pieces. In the event that a participant could not complete a level, the experimenter restarted the game at the level at which the participant began. This occurred rapidly (under 3 seconds). Despite individual differences in game playing experience, no participant advanced beyond level 3 during the Easy condition or level 11 during the Hard condition.

Data Collection and Signal Processing.

Scalp EEG was collected using tin electrodes housed within a stretchable lycra cap, (Electro-Cap International, Inc.). Data were acquired from 30 sites referenced to linked earlobes and a common ground (FPz). Electrode placement was adapted from the 10-20 international system (Jasper, 1958). Additional electrodes were placed above and below the right eye over the orbicularis oculi muscle and the outer canthi of both eyes to record eyeblinks. Impedances were kept below 10 k Ω throughout the experiment. All channels were amplified 500 times using Neuroscan Synamps 1, linked to Neuroscan acquisition/edit software (version 4.3). Online bandpass filters were set at .01-100 Hz with a sampling rate of 1,000 Hz. Offline, data were processed with the Neuroscan software. A zero-

phase shift low-pass filter at 50 Hz (24 dB octave/slope) was applied followed by an ocular artifact algorithm (Semlitsch et al., 1986). Data from each condition were epoched into 1-s sweeps. These epochs were linear detrended and baseline corrected using the mean of the pre-stimulus interval. Epochs containing amplitudes of more than 75 μV were discarded, the data were spline fit (1024 data points). Spectral average was calculated across 1-Hz bins and averaged across the frequency bandwidths delta (1 -3 Hz), theta (3 – 8 Hz), lower alpha (8 – 10 Hz), upper alpha (10 – 13 Hz), beta (13 – 30 Hz), and gamma (30 – 44 Hz) for the following electrode sites: F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2. These averages were then natural log transformed prior to statistical analysis. Coherence was defined as $C_{xy}(f)^2$ and computed across 1-Hz bins and averaged across the frequency bandwidths theta (3 – 8 Hz), alpha (8 – 13 Hz), lower beta (13 – 20 Hz), and upper beta (20 – 30 Hz) between electrode Fz, which overlies the premotor region, and the following electrodes: F3, F4, C3, C4, T3, T4, P3, P4, O1, and O2. All coherence values were subjected to a Fisher z-transformation prior to statistical analysis to approximate a normal distribution. Please see Figure 1 for a graphical description of the experimental setup and montage.

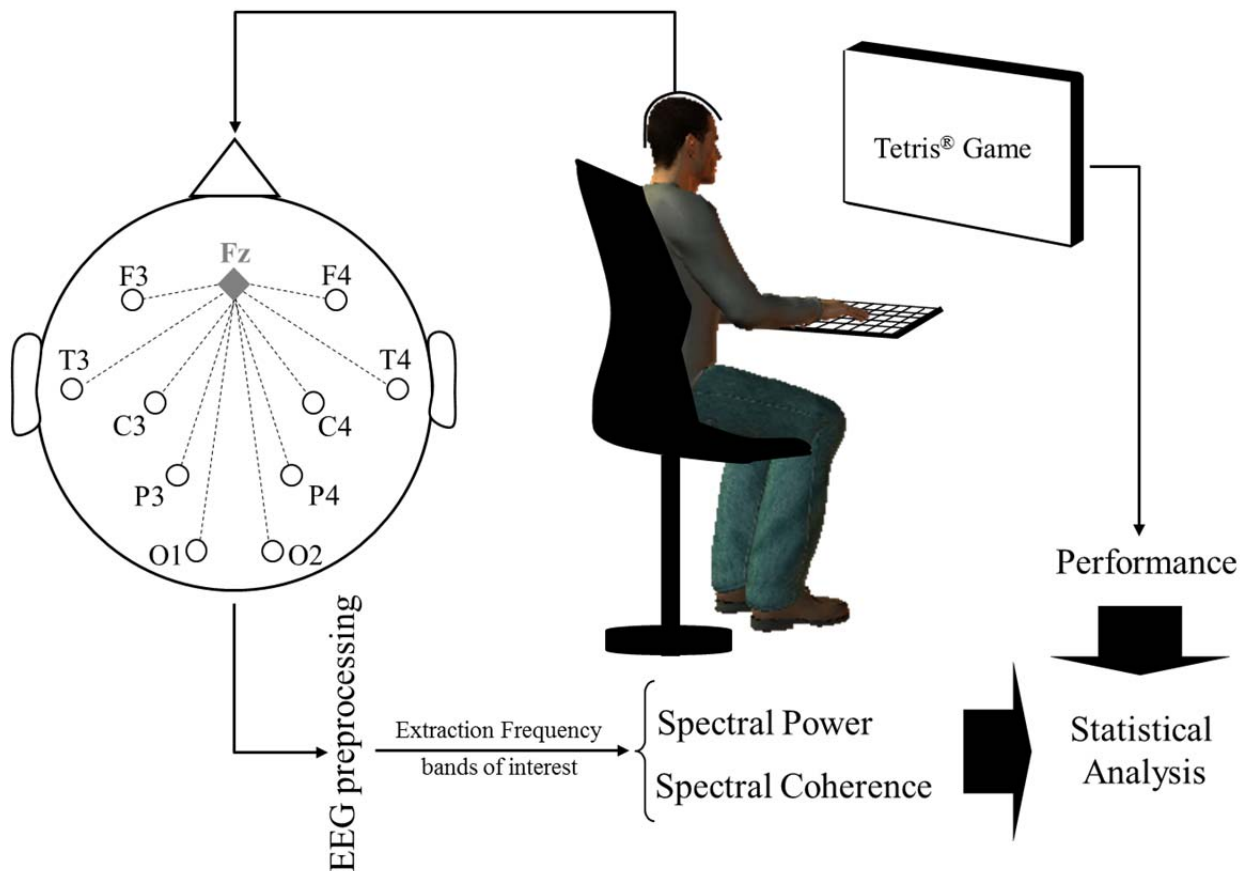


Figure 1. Experimental setup. The scalp montage reflects those electrodes included in the spectral power analyses. Additionally, the pairing of each electrode to the shaded diamond (Fz electrode) is representative of the coherence analyses.

Statistical Design.

Spectral averages and coherence values for the aforementioned bandwidths were subjected to separate 2 x 2 x 5 (Condition x Hemisphere x Region) repeated measures ANOVAs. Significant interaction effects were followed by Student Newman-Keuls post-hoc tests. Conventional degrees of freedom are reported throughout the results, and the Huynh-Feldt correction is provided when sphericity was violated. The p-values reported are based upon the corrected degrees of freedom. The a priori predictions for frontal theta and

parietal upper-alpha were assessed using separate paired sample t-tests. For theta, left frontal (F3) during the Easy condition was compared to left frontal (F3) during the Hard condition. Right frontal (F4) was also compared between the Easy and Hard conditions. For upper alpha, similar analyses were run for left and right parietal regions (P3 & P4, respectively). Cohen's *d* effect sizes are also provided when appropriate.

Results

Performance Results.

A paired sample t-test revealed that participants failed to complete a level more frequently during the hard condition ($M = 2.3$) than the easy condition ($M = 0.15$) ($t(19) = 10.302$, $p < .001$), suggesting a successful manipulation of difficulty.

Spectral Power Results.

Delta. No significant results for contrasts of interest were found for the delta bandwidth.

Theta. Theta synchrony as a function of task difficulty showed an elevation that approached significance ($F(1,19) = 3.98$; $p = 0.061$; $d = 0.045$). Additionally, the a priori prediction that frontal theta would significantly increase in the Hard condition relative to the Easy condition was confirmed exclusively for the right hemisphere ($t(19) = 2.99$; $p = 0.008$; $d = 0.205$), see Figure 2A.

Lower Alpha. No significant results for contrasts of interest were found for the lower alpha bandwidth.

Upper Alpha. The statistical analysis revealed a significant main effect of condition for the upper alpha bandwidth ($F(1,19) = 6.17$; $p = 0.022$; $d = 0.064$). This effect revealed upper alpha desynchrony due to an increase in task difficulty. However, the main effect was superseded by a significant Condition x Region interaction ($F(1,19) = 3.18$; $p = 0.047$; $\epsilon = 0.558$). This interaction revealed that the upper alpha desynchrony during the Hard condition was confined to the

central ($p < 0.001$; $d = 0.142$) and parietal regions ($p = 0.01$; $d = 0.110$), see Figure 2B. Additionally, the a priori prediction that parietal upper alpha desynchrony would significantly increase due to task difficulty was confirmed in both hemispheres (left hemisphere: $t(19) = 4.56$; $p < 0.001$; $d = 0.085$; right hemisphere: $t(19) = 3.13$; $p < 0.001$; $d = 0.119$).

Beta. Beta synchrony due to task difficulty showed an elevation that approached significance ($F(1,19) = 2.68$; $p = 0.059$; $\epsilon = 0.709$), thus post-hoc analyses were conducted. These analyses revealed beta synchrony in the occipital regions during the Hard condition ($p < 0.001$; $d = 0.102$), see Figure 2C.

Gamma. The statistical analysis revealed a significant Condition x Region interaction for the gamma bandwidth ($F(1,19) = 4.12$; $p = 0.012$; $\epsilon = 0.711$). This interaction revealed gamma synchrony due to task difficulty, but that this increase was confined to the temporal ($p = 0.03$; $d = 0.122$), parietal ($p = 0.041$; $d = 0.094$), and occipital regions ($p = 0.002$; $d = 0.231$), see Figure 2D.

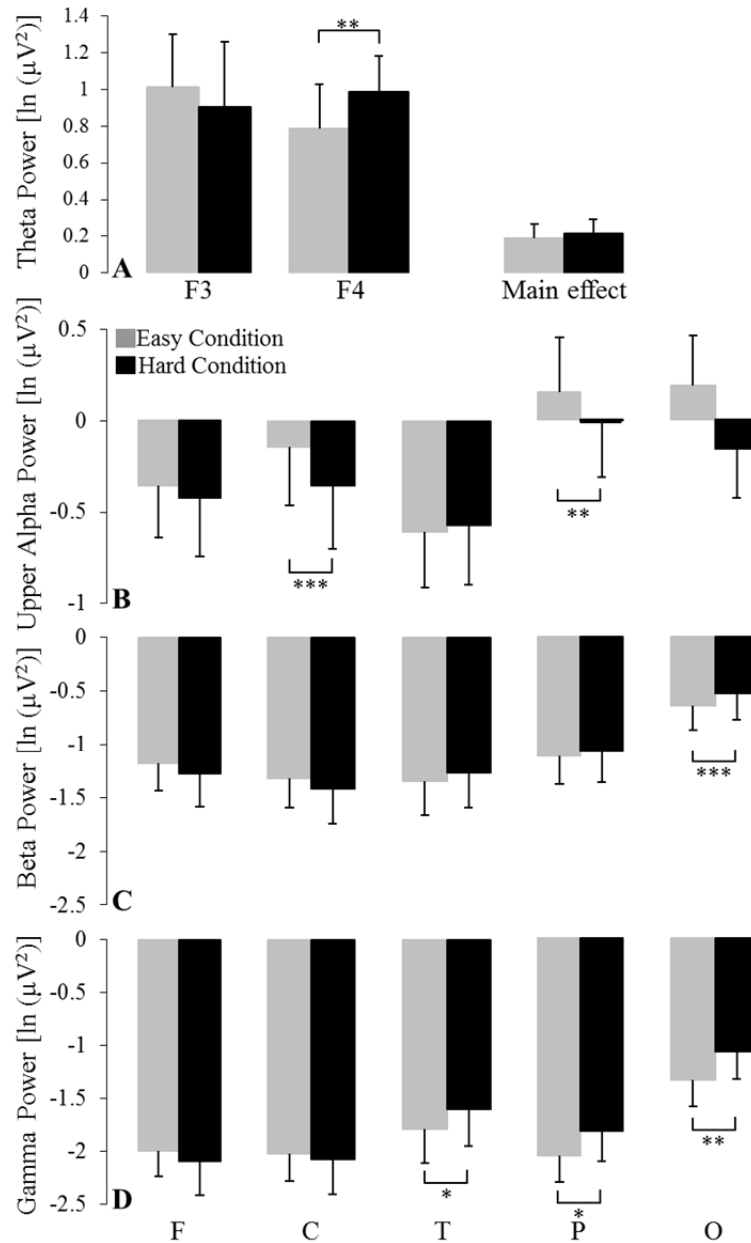


Figure 2. Spectral power results. A. Theta power results for the a priori contrasts (comparing Easy and Hard conditions at the frontal regions) and the ANOVA main effect. B., C., D., Each graph corresponds to a different frequency bandwidth, Upper Alpha, Beta, and Gamma, respectively. Each contrast compares Easy and Hard conditions at each of the five regions, frontal (F), central (C), temporal (T), parietal (P), and occipital (O), * $p < .05$, ** $p < .01$, * $p < .001$.**

Coherence Results.

The statistical analysis revealed a significant main effect for condition for all bandwidths (theta: $F(1,19) = 7.57$; $p = 0.013$; $d = 0.411$; alpha: $F(1,19) = 11.63$; $p = 0.003$; $d = 0.359$; lower beta: $F(1,19) = 14.60$; $p = 0.001$; $d = 0.469$; upper beta: $F(1,19) = 22.93$; $p < 0.001$; $d = 0.611$). These main effects revealed that coherence was greater in the Hard condition than in the Easy condition, see Figure 3.

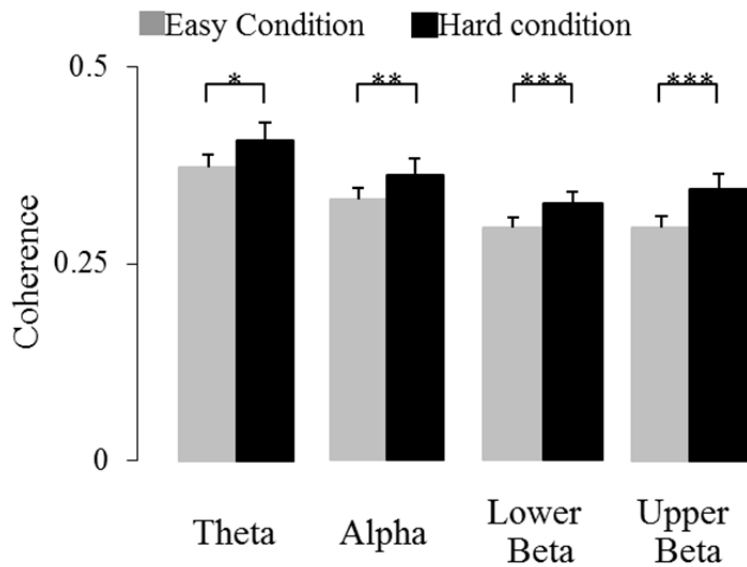


Figure 3. Spectral coherence results comparing Easy and Hard conditions for each of the four frequency bandwidths, * $p < .05$, ** $p < .01$, * $p < .001$.**

Discussion

As predicted, with increased cognitive-motor task difficulty, elevations in neural effort as indexed by both regional cerebral-cortical activation and networking were observed. Given that these increases happened in tandem with decreases in task performance, these findings support the psychomotor efficiency hypothesis. The spectral results replicate aspects of Sauseng et al. (2007), Muzuki et al. (1982), and Serman and Mann (1995), in that frontal theta synchrony and parietal upper alpha desynchrony occurred resultant to increased cognitive-motor task difficulty. This replication was anticipated because of the functional neuroanatomical associations of frontal theta synchrony with attentional engagement and parietal upper alpha desynchrony with multimodal sensory integration. Both of these processes are required to a greater degree as the difficulty of Tetris® increased.

Additionally, the results of this study advance the prior EEG spectral findings in cognitive-motor task performance through its examination across the scalp topography in multiple bandwidths. First, the results reveal a tendency for theta synchrony due to an increase in task difficulty regardless of region. These results are consistent with the visuomotor task performance work of Rebert, Low, & Larsen (1984). Further, when limiting the theta band statistical analysis to the frontal region, it was found that increases in task difficulty resulted in frontal theta synchrony which was driven by the right hemisphere. This result is consistent with findings of right hemisphere dominance during visuomotor performance (see Hatfield, Landers, & Ray, 1984; Rebert et al.) and suggests that frontal

asymmetry may be a component of the enhanced cortical processing necessitated by increasing task difficulty. Additionally, since modulations in frontal asymmetry have been associated with changes in affect (see Davidson, 1984), it is possible that the observed asymmetry could be a result of changes in task difficulty and/or changes in affect.

Second, the findings reveal a positive relationship between upper alpha desynchrony and task difficulty in both the parietal and central regions. These results are consistent with the noted association between upper alpha desynchrony and increased cortical activation due to task-specific demands (see Pfurtscheller, Stancak, & Neuper, 1996). The present study's findings are also consistent with the central and parietal regions involvement in multimodal sensory integration, object recognition, and the sensorimotor transformations necessary to act upon the recognized objects, all of which are cognitive motor processes demanded by Tetris® (Goodale & Milner, 1992; Kerick, Hatfield, & Allender, 2007; Klemisch, 1999). Of note, no changes in lower alpha synchrony due to condition were observed. Lower alpha synchrony is believed to index changes cortical activation due to general arousal as opposed to the changes in arousal induced by task-specific demands associated with upper alpha synchrony (see Kerick, Hatfield, & Allender, 2007; Klemisch, 1999). This specificity of significant results to the upper alpha bandwidth indicates that levels of general arousal were held constant while exclusively manipulating task-specific demands.

Third, the results reveal beta synchrony in the occipital region during the Hard task condition relative to the Easy condition. Beta synchrony has been

associated with active task engagement and the occipital cortex houses the primary visual processing areas (Singer, 1993). Additionally, occipital beta synchrony has been associated with visual perception (Piantoni, Kline, & Eagleman, 2010). Thus, the observed occipital beta synchrony may be due to the augmented rate of stimuli presentation and consequent increased perceptual demands during the Hard condition.

Fourth, the results demonstrate gamma synchrony in the parietal, occipital, and temporal regions during the Hard condition. Gamma activity is associated with localized sensory integration and has been observed to increase with sensory processing demands (von Stein & Starnthein, 2000). Right temporal activity is indicative of visuospatial processing, and the functions of the parietal and occipital regions have already been noted (Goodale & Milner, 1992; Hatfield et al., 1984). Due to the high degree of sensory integration, particularly visuospatial processing, required by Tetris® in order to process the game pieces, gamma synchrony in these cortical regions during the Hard condition seems reasonable.

Collectively, the observed changes in spectral power within multiple bandwidths and across the scalp topography along with the concomitant decrement in performance due to a more difficult task condition support the psychomotor efficiency hypothesis in that excessive neural effort is accompanied by decreased cognitive-motor performance.

While the spectral power findings illustrate increases in neural activation as a function of task difficulty, they focus on specific brains in isolation. Given the consensus that the brain operates through dispersed interconnected regions (see

Laughlin & Sejnowski, 2003; Sporns et al., 2005), it is surprising that we were unable to find any previous reports of changes in the cortical networking due to alterations cognitive-motor task difficulty. In this regard, increased cortical networking, as indexed by EEG coherence, between the motor, sensory, and executive brain regions and the premotor region across all frequency bandwidths examined was observed. Information about how and where to maneuver the game pieces is communicated to the premotor region from sensory and executive regions, and the final motor commands to execute the movement of game pieces must be communicated from the premotor region to the motor region. Thus, the results demonstrating increased networking between the sensory, executive, and motor regions with the premotor region seem reasonable. Additionally, the results occurred in bandwidths (theta, alpha, lower beta, & upper beta) previously found to be involved in the long-range cortical networking required for communication between the aforementioned brain regions (von Stein & Sarnthein, 2000). These results demonstrating increased cortical networking due to an increase in task difficulty are in accord with the psychomotor efficiency hypothesis given that such unrefined networking occurred concomitant with reductions in task performance.

The present findings are directionally consistent with the expertise/learning and performance literature, which has revealed reductions in coherence underlying superior performance (Bell & Fox, 1996; Busk & Gailbrith, 1975; Deeny et al., 2003; Reiterer et al., 2005). Additionally, while previous work only reported changes in cortical networking between specific electrode sites for

specific frequency bandwidths (e.g., reductions specific to T3-Fz within the lower-alpha and lower-beta frequency bandwidths in Deeny et al.), the present study observed generalized alterations in cortical networking to Fz (motor region) in all observed bandwidths.

This study replicates and expands beyond findings demonstrating increases in neural activation as a function of cognitive-motor task difficulty. Crucially, the present study is the first to report changes in the cortical networking due to modulating the difficulty of the task while holding expertise constant. The psychomotor efficiency hypothesis suggests that excessive levels of neural activation and non-essential cortical networking may underlie decrements in cognitive-motor performance; yet, this relationship had not been well characterized. The present study's cortical activation and networking analyses along with their relationship to performance levels support this central notion of the psychomotor efficiency hypothesis.

The present study's findings elucidate how EEG-indexed changes in cortical dynamics may provide a window to the psychophysiological mechanisms that underlie the variability observed in cognitive-motor performance. Importantly, the results also inform the popular interest in measuring cognitive workload (see Shanker & Richtel, 2011). Increases in task difficulty are accompanied by increases in cognitive workload, which, when measured using EEG, has historically been indexed by the event-related potential technique or spectral power. Given that the present results reveal coherence to be more sensitive, as indicated by effect size, to changes in task difficulty than spectral

power, future studies may want to explore the use of coherence as a method for gauging cognitive workload. A deeper understanding of the relationship between cortical dynamics and cognitive-motor performance may inform the measurement of cognitive workload and aid in the design of techniques aimed at enhancing performance even across a wide range of task difficulty.

Study 2

A novel approach to the physiological measurement of mental workload

Abstract

While performing a visuo-motor task under incrementally-varied levels of difficulty, individuals were probed with a variety of novel, task-irrelevant, auditory stimuli. To determine the effect of task load on cerebral-cortical processing of these stimuli, event-related potentials were recorded while participants performed the task. We found that N1, P2, P3 and late positive potential (LPP) component amplitudes were inversely related to task-difficulty. This suggests that a variant of the oddball paradigm – in which the stimulus stream comprises novel sounds – is capable of providing a reliable index of mental workload.

Introduction

The efficient allocation of neural resources is crucial while individuals perform mentally demanding tasks. Such a need is based on the inverse relationship between mental workload and attentional reserve (Wickens et al., 1983), which when depleted can be expected to limit cognitive processing for any additional demands, resulting in performance decrement. Thus, the manner by which neural resources are allocated during the performance of a task is a question of fundamental interest. Such an understanding is dependent upon the attainment of an objective measure of mental workload.

Beginning with the seminal work by Wickens et al. (1977), a number of studies have employed the event-related potential (ERP) technique to assess mental workload. These early efforts (e.g., Isreal et al., 1980a; Isreal et al., 1980b; Kramer et al., 1987; Sirevaag et al., 1989; Wickens et al., 1983) employed dual-task paradigms in which ERPs to a secondary task were measured while participants performed a primary task of interest (e.g., attending to auditory stimuli while solving arithmetic problems as the primary task). Many of these studies revealed an inverse relationship between amplitude of the parietal-P3 component and difficulty of the primary task. However, such dual-task paradigms are not optimal for assessing the mental workload required by a primary task given that the addition of a secondary task may inherently change the primary task, thus compromising the assessment of the demand it imposes (Kramer et al., 1985).

In order to avoid the limitation of dual-task paradigms, ERPs to task-irrelevant stimuli should be measured while participants focus exclusively on a given task (Papanicolaou and Johnstone, 1984). Several studies have employed such an irrelevant-probe technique and reported decreases in N1 and/or P3 component amplitudes with changes in task difficulty (Bauer et al., 1987; Kramer et al., 1995; Sirevaag et al., 1993; Ullsperger et al., 2001; Wilson and McCloskey, 1988). However, some of these studies used visual probes, which may not have been detected by participants (e.g., Bauer et al., 1987; Wilson and McCloskey, 1988), while others did not observe graded difficulty-dependent changes with respect to task load (e.g., Kramer et al., 1995) or were limited in the number of participants and recording sites analyzed (Sirevaag et al., 1993). As such, further research employing the task-irrelevant probe technique was warranted.

Building upon the previous work, recent studies have also employed task-irrelevant probes to measure mental workload (e.g., Allison and Polich, 2008; Ullsperger et al., 2001). Ullsperger et al. (2001) challenged participants in 4 task conditions: an oddball task, a visuo-motor task, an arithmetic task, and a simultaneous performance of the visuo-motor and arithmetic tasks. Throughout each condition participants were presented with common and rare pure tones as well as rare novel sounds. The authors reported greater parietal-P3 amplitude to rare tones and greater novelty-P3 amplitude to novel sounds during the oddball task relative to the other 3 conditions. Further, the novelty-P3 tended to decrease slightly as a function of task complexity (although this trend failed to reach statistical significance), whereas this trend was not observed for the parietal- P3.

This finding supports novel sounds as being advantageous over pure tones in gauging mental workload. The lack of a significant graded difficulty-dependent effect may be due to the fact that task difficulty was manipulated by having participants perform one of two primary tasks in two separate blocks, and in a third block having them simultaneously perform both tasks. It seems reasonable to suggest that incrementally varying the difficulty of a single primary task might be more efficacious in demonstrating significant monotonic differences in relation to task difficulty.

More recently, Allison and Polich (2008) published a study using the task-irrelevant probe technique (specifically, a modified oddball using pure tones) in which the difficulty of a single task was incrementally varied. In this study, participants viewed a video game and also played the game at easy, moderate and hard levels of difficulty. Although the authors reported a significant reduction in the amplitude of a number of ERP components between play (regardless of difficulty) and view conditions, they found little evidence of reductions with respect to changes in game difficulty. Specifically, the authors reported larger P2, N2, and P3 component amplitudes during the view condition relative to all the playing conditions as well as a decrease in N2 amplitude during the hard condition relative to the medium condition. It is possible that the lack of significant graded difficulty-dependent differences in component amplitude might be attributable to the relatively low salience of pure tones, resulting in modest attentional capture (Friedman et al., 2001).

Therefore, in the present study we combined the strengths of the approaches taken by Allison and Polich, 2008) and (Ullsperger et al., 2001). Specifically, we used a single task that was incrementally varied with respect to difficulty while probing participants with novel sounds. We reasoned that novel stimuli would be more successful in indexing mental workload as they have been shown to be more effective in capturing attention than simple tones. The superior efficacy of the novel stimuli is due to their resemblance to real-world compulsory attention capture by novel or unexpected events (Friedman et al., 2001). In the current study participants played Tetris®, a video game that requires executive control (planning), visual–spatial processing, and motor execution under two levels of difficulty, and in a third condition viewed the game, but did not engage in play. Throughout each condition participants were intermittently presented with a set of novel, task irrelevant, auditory stimuli (e.g., a woman coughing, the sound of breaking glass). One-second epochs of the EEG time-locked to each of the auditory stimuli were extracted and the resultant epochs were averaged within each condition. Based on the prior literature, we predicted that the amplitude of ERP components elicited by the probes would be inversely related to task difficulty.

Materials and Methods

Participants

Twenty-three, right-handed young adults (11 women) were recruited from a large Mid-Atlantic metropolitan area. Because the data from three of the participants were discarded due to poor electrophysiological recordings, the final sample was comprised of 20 individuals (10 women, with an age range of 20–33, $M = 24.4$, $SD = 4.1$ years). Tetris® playing experience ranged from never having previously played to having played more than 50 h. All participants provided informed written consent.

Procedures

Participants were seated in front of a 15" monitor and played Tetris® while the song “Korobeiniki” (“Music A” in the standard Tetris® game) was played (72–76 dB SPL) from a speaker next to the monitor. During the view condition participants fixated on a paused game while the music continued to play. During the easy and difficult conditions, game play began at levels 1 and 8, respectively. After completing a level (i.e., completing 10 lines), the participants immediately advanced to the next level of the game. For each successive level, the game became more difficult due to an increased rate of speed with which the game pieces fell. Although the game allows the player to manually increase the speed of the pieces, speed was held constant within a level as the participants were instructed not to manually advance the pieces. The change in speed was thought to impact upon mental workload as the participants had to more quickly

decide where to place the current piece, execute the placement, and update their planning for the successive pieces. In the event that a participant could not complete a level, the experimenter restarted the game at the level at which the participant began. This occurred rapidly (under 3 s) so as to minimize the probability of a sound being presented during this interruption. A paired sample *t*-test revealed that there were more restarts during the hard condition ($M = 2.3$) than the easy condition ($M = 0.15$) ($t(19) = 10.302$, $p < 0.001$), suggesting a successful manipulation of difficulty. Despite individual differences in game playing experience, all participants ranged between levels 1 and 3 during the easy condition and between levels 8 and 11 in the hard condition.

In each experimental condition, participants were probed with a set of 30 familiar auditory stimuli randomly selected from a larger collection obtained from the New York State Psychiatric Institute (Fabiani et al., 1996). The stimuli were presented in random order (87–96 dB SPL; interstimulus interval = 6–30 s.) from two speakers positioned 70 cm behind the participants.

Data collection and signal processing

Scalp EEG was collected using tin electrodes housed within a stretchable lycra cap, (Electro-Cap International, Inc.). Data were acquired from 30 sites referenced to linked earlobes and a common ground (FPz). Electrode placement was adapted from the 10–20 international system (Jasper, 1958). Additional electrodes were placed above and below the right eye over the orbicularis oculi muscle and the outer canthi of both eyes to record eyeblinks. Impedances were kept below 10 k Ω for electrodes of interest (Fz, Cz, and Pz) throughout the

experiment. All channels were amplified 500 times using Neuroscan Synamps 1, linked to Neuroscan acquisition/edit software (version 4.3). Online bandpass filters were set at .01–100 Hz with a sampling rate of 1000 Hz. Offline, data were processed with the Neuroscan software. After setting a zero-phase shift low-pass filter at 20 Hz (24 dB octave/slope), an ocular artifact algorithm was applied (Semlitsch et al., 1986). ERPs were obtained by extracting the epoch of 100 ms prior to stimulus onset through 900 ms post-stimulus, then baseline corrected with reference to the pre-stimulus interval. Next, each of the 30 trials was visually inspected and any trials containing marked artifact were excluded from subsequent analysis. The remaining trials were then averaged. Each ERP was based on at least 20 trials. The mean amplitude for each component was calculated using the approach suggested by Handy (2005), which recommends the use of narrow time windows centered around the peaks of the components in the grand average waveform. Accordingly, the time windows used were as follows: N1 = 140–160 ms; P2 = 225–255 ms; P3 = 290–320 ms; LPP = 570–610 ms for each of the three midline electrodes of interest (Fz, Cz, and Pz).

Statistical design

Mean amplitude of each component was subjected to separate 3×3 (Condition \times Electrode) repeated measures ANOVAs. Significant interaction effects were followed by one-way ANOVAs applied to each electrode. Finally, all simple mean effects were determined using paired *t*-tests. Conventional degrees of freedom are reported throughout the results, and the Greenhouse–Geisser correction is provided when sphericity was violated. The *p*-values reported are

based upon the corrected degrees of freedom. Additionally, Cohen's *d* effect sizes are also provided when appropriate.

Correlational analyses were also conducted between Tetris experience and all component amplitudes as well as Tetris performance and all component amplitudes.

Results

Fig. 1A illustrates the grand average ERPs recorded from the midline electrodes Fz, Cz, and Pz for each condition. The N1, P2, P3, and LPP (late positive potential) components are evident. The statistical analysis revealed a Condition \times Electrode interaction for the N1 component ($F(4,76) = 4.072$; $p = 0.013$, $\epsilon = 0.685$), the P3 component ($F(4,76) = 5.371$; $p = 0.004$; $\epsilon = 0.650$) and the LPP component ($F(4,76) = 4.891$; $p = 0.001$). Additionally, there was a main effect for Condition for the P2 component ($F(2,38) = 6.026$; $p = 0.010$, $\epsilon = 0.757$).

N1 component

Post hoc analyses revealed that for the N1 at the Cz electrode, the mean amplitude was significantly larger in both the view and easy conditions than in the hard condition (Fig. 1B) (view > hard, $p = 0.003$, $d = 0.717$; easy > hard, $p = 0.045$, $d = 0.473$). The N1 component is believed to reflect compulsory, early sensory processing, exhibit a frontocentral scalp distribution, and be sensitive to attention (Hillyard et al., 1973; Parasuraman and Beatty, 1980).

P2 component

Post hoc analyses revealed that for the P2 regardless of electrode, the mean amplitude was significantly larger in both the view and easy conditions than in the hard condition (Fig. 1B) (view > hard, $p < 0.01$, $d = 0.740$; easy > hard, $p < 0.05$, $d = 0.697$). Like the N1, the P2 component is believed to reflect compulsory, early sensory processing and exhibit a frontocentral scalp

distribution, and be sensitive to attention (Peters et al., 2005; Picton and Hillyard, 1974).

P3 component

As predicted, mean amplitudes of the P3 at the Pz electrode differed across all three experimental conditions in a graded difficulty-dependent manner (Fig. 1B) (view > easy, $p = 0.046$, $d = 0.402$; view > hard, $p = 0.003$, $d = 0.906$; easy > hard, $p = 0.012$, $d = 0.674$). The P3 is believed to represent non-obligatory, cognitive evaluation of stimuli and generate a parietal maximal distribution (Parasuraman and Beatty, 1980; Ruchkin et al., 1988). Importantly, the P3 at Pz reflects cognitive processes independent of variations in motor processes (Makeig et al., 2004).

LPP component

Like the P3, mean amplitudes of the LPP at the Pz electrode differed across all three experimental conditions in a graded difficulty-dependent manner (Fig. 1B) (view > easy, $p = 0.003$, $d = 0.652$; view > hard, $p < 0.001$, $d = 1.717$; easy > hard, $p = 0.004$, $d = 1.037$). Similar to the P3, the LPP is believed to represent non-obligatory, cognitive evaluation of stimuli and generate a parietal maximal distribution (Ruchkin et al., 1988). However, it has been reported much less frequently in the literature than the P3. See Table 1 for all means and post hoc analyses.

The correlational analysis revealed that neither Tetris® experience nor task performance was significantly correlated with any of the ERP component amplitudes.

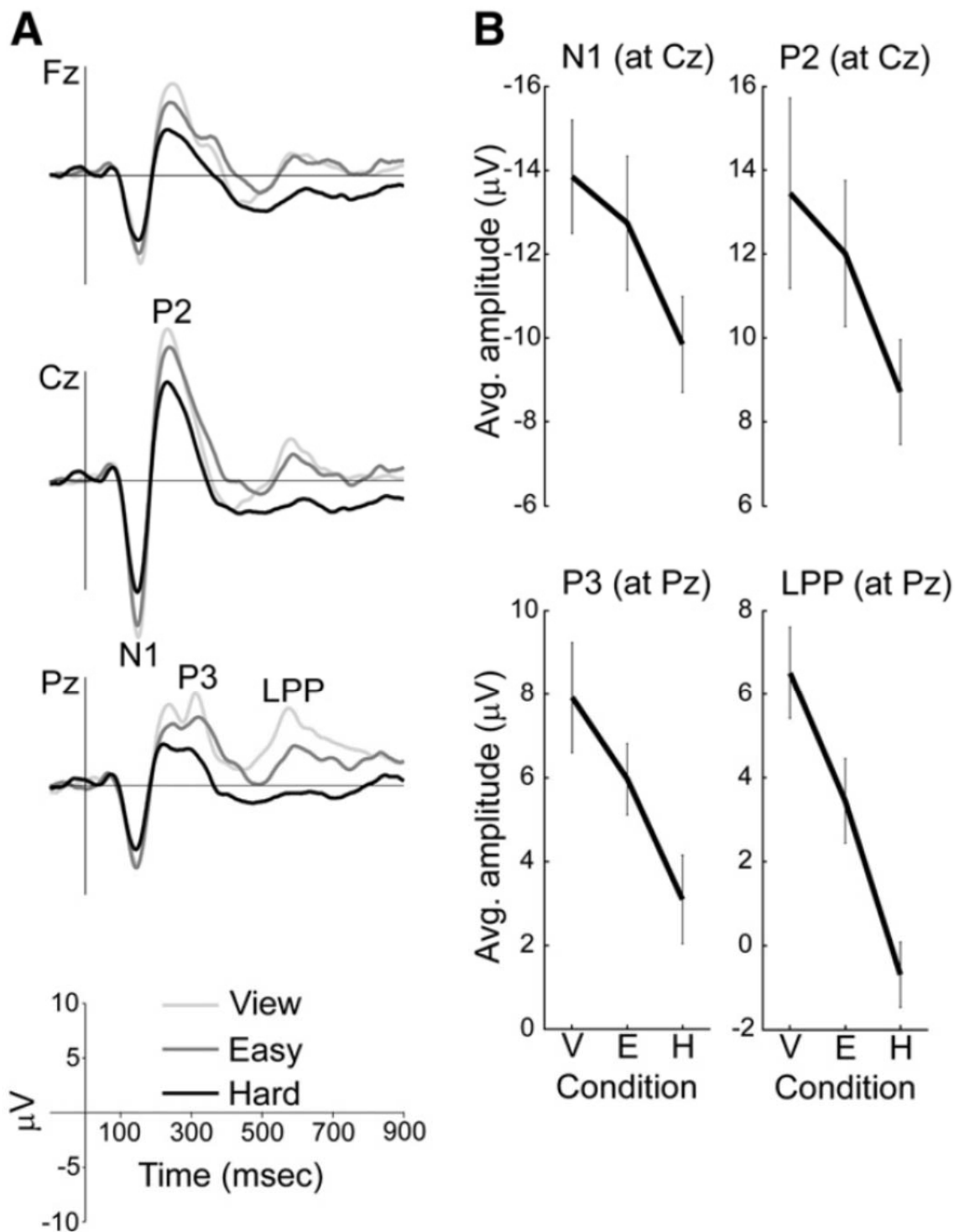


Fig. 1. A) Grand-average ERPs recorded from the Fz, Cz and Pz electrode locations time-locked to the auditory probes. Data from the three experimental conditions are superimposed. B) Average amplitude of the N1, P2, P3 and LPP components as a function of experimental condition (View, Easy, and Hard).

Table 1
Means and summary of statistical results.

Component	Electrode	Condition		
		View	Easy	Hard
N1	Fz	-7.425	-6.933	-5.815
	Cz	-13.844	-12.738	-9.846 ^{a, b}
	Pz	-6.871	-7.090	-5.454
P2	Main Effect	9.632	8.030	5.419 ^{a, b}
P3	Fz	4.034	4.040	2.224 ^{a, b}
	Cz	6.220	7.102	3.940 ^b
	Pz	7.918	5.964 ^a	3.094 ^{a, b}
LPP	Fz	1.893	1.578	-1.756 ^{a, b}
	Cz	3.481	2.181	-2.026 ^{a, b}
	Pz	6.513	3.445 ^a	-0.699 ^{a, b}

^a Significantly different from view.

^b Statistically different from easy.

Discussion

For more than three decades, researchers have been using the ERP technique to measure mental workload. The assessment protocols were greatly improved with the use of the task-irrelevant probe technique. Two contemporary studies have further advanced the measurement of mental workload by incrementally-varying task difficulty or using intermittently presented novel sounds (Allison and Polich, 2008 and Ullsperger et al., 2001, respectively). The present study combined elements of these two innovations by incrementally-varying task difficulty while probing participants with novel, task-irrelevant auditory stimuli. The results demonstrate the utility of this ERP paradigm in indexing mental workload. Unlike many of the prior efforts to index workload, the present approach provided compelling evidence of an inverse relationship between incremental changes in task load and ERP component amplitude. Due to their psychometric similarity, the Easy vs. Hard comparison was this study's critical contrast of interest. All of the evaluated ERP components differed significantly between the Easy and Hard conditions. Additionally, the P3 and LPP differed among all three conditions suggesting that these components may be the most sensitive (in terms statistical significance and effect sizes) to changes in task difficulty. While modulation of P3 amplitude as a function of task difficulty has been previously reported (Kramer et al., 1987, 1995; Isreal et al., 1980a; Isreal et al., 1980b; Wickens et al., 1977; Sirevaag et al., 1989, 1993), the LPP appears to have provided the most robust index of task load. However, this component is not

well-characterized in the literature. Thus, the present findings indicate that future investigation of the LPP is warranted.

The P3 and LPP components are more sensitive to changes in mental workload than the N1 and P2 components. However, it is possible that early cognitive processing, as indexed by N1 and P2, influences these latter components (P3 and LPP). Specifically, given that mental workload is inversely related to attentional reserve and N1 and P2 have been shown to be modulated by attention (Hillyard et al., 1973; Picton and Hillyard, 1974), it is likely that the reduction in N1 and P2 represent a reduction in the allocation of attention to the probe stimuli. This putative reduction in attentional resource allocation can be expected to diminish the stimulus information available to the higher order processes indexed by P3 and LPP, leading to a further reduction in amplitude of these components as well.

The detection of graded difficulty-dependent reductions in the ERP in the present study likely resulted from taking advantage of select innovations developed by Allison and Polich (2008) and Ullsperger et al. (2001). Specifically, the use of novel, environmental sounds, as opposed to pure tones, appears to have elicited increased electro-cortical activity to the sounds. Additionally, incrementally varying the difficulty on a single task, as opposed to switching tasks or concurrently performing multiple tasks, likely facilitated the detection of monotonic differences in relation to task load. Future work should examine more gradations of task difficulty to determine if reductions in electrocortical activity

are concomitant with increases in mental workload when performance remains relatively stable.

This measure of mental workload has broad implications and is also easy to implement in that it requires a small number of trials (30) to generate an informative index. Notably, such a measure could be employed to assess the demands of various cognitive tasks (e.g., reading, operating a machine) which could then be applied to various learning environments and human-machine interfaces. In summary, the present effort provided a unique contribution to the assessment of mental workload using the ERP technique. By building upon previous innovations, the current study was able to capture graded difficulty-dependent reductions in the ERP.

Study 3—Dissertation Project

Psychophysiological investigation of attentional processes during motor learning

Abstract

As one becomes more proficient at a motor task the attentional demand required to perform that task decreases. Behavioral evidence suggests that experienced individuals possess greater attentional reserve during task execution compared to novices, such that, they are better able to cope with additional, possibly unexpected, challenges. This advantage may be the result of streamlining the neural processes underlying motor planning and execution over the course of learning. Such psychomotor efficiency reduces the demand on cortical resources imposed by the primary task such that they are available for coping with challenge beyond that of the task. However, this hypothesis has not been tested. The aim of this study was to provide neurobiological evidence of the positive relationship between motor skill and attentional reserve.

Twenty-one participants were randomly assigned to one of two groups, a group that learned a novel visuomotor distortion task, and a control group that performed the same task with no distortion (i.e., no learning). For the duration of the task, event-related brain potentials (ERPs) elicited by a set of novel stimuli were recorded. The dynamic modulation of ERP component amplitude was used as an index of attentional reserve. We predicted that component amplitudes would initially be diminished in the learning group relative to the control group, but that there would be a progressive increase in amplitude as a function of learning; by contrast, we predicted that ERP component amplitudes would remain relatively stable in the control group.

Importantly, task performance, as measured by initial directional error, was initially worse in the learning group relative to control group and significantly improved over the course of exposure, whereas the control group's performance was stable. This suggests the visuomotor distortion task employed was successful in serving as a model of motor skill acquisition. Analyses of the ERPs elicited by the auditory probes revealed that the exogenous components, N1 and P2, were not different between the two groups and did not change over the course of learning suggesting that early sensory processing was comparable between the two groups. Notably, the novelty P3 component—an index of the involuntary orienting of attention--was initially attenuated in the learning group relative to the control group, but progressively increased in amplitude as a function of learning in the learning group only. This suggests that attentional reserve increased as a function of motor skill acquisition, such that greater attentional resources were available to process the auditory probes.

The current study provides psychophysiological evidence that attentional reserve increases as a function of motor skill acquisition. Moreover, the metric developed for this study provides a means to assess cognitive/motor learning in both applied cognitive and clinical domains.

Introduction

As one learns a novel motor task the effort required to execute the demands is reduced even though the requirements remain constant, resulting in efficient use of attentional and physiological resources as one becomes proficient. Efficiency is characterized by the effort required for work output and can be quantified by increased force per motor unit (Aagaard et al., 2002), enhanced inter-limb coordination (Lay, Sparrow, Hughes & O'Dwyer, 2002), streamlined neural resource allocation (Hatfield & Hillman, 2001; Hatfield et al., 2004), greater focus on task-relevant cues (Williams, 2002), etc. Coinciding with changes in efficiency are changes in attentional processes. Phenomenological reports and behavioral studies posit a positive relationship between increasing proficiency and attentional reserve (Magill, 2007). Specifically, he suggests that attentional demands are high during the early stage of motor learning, but become reduced as one becomes skilled. However, physiological evidence of the dynamic relationship between attention and motor learning is limited.

Attention: capacity and reserve.

Attention refers to the directed allocation of an individual's cognitive resources and is limited in regards to amount; the total quantity available is referred to as attentional capacity (Schmidt & Wrisberg, 2008). As one engages in a task, attentional resources are drawn from the attentional capacity, leaving a finite amount of attentional reserve. Reserve is further consumed when responses to additional tasks are initiated. In other words, there is an attentional 'cost'

associated with each task that is being performed. Additionally, more complex tasks require greater attentional demand compared to simple tasks. If attentional resources are low, performance on one or multiple tasks may suffer (Strayer, Drews, & Johnson, 2003, Magill, 2007). However the attentional ‘cost’ for a given task is not fixed. Fitts and Posner (1967) hypothesized that as one becomes skilled there is a shift from controlled processing during which motor sequences are held in working memory to automatic processing where motor sequences become routine, thus decreasing the attentional demand associated with a given task’s execution.

Attentional dynamics and motor learning.

Supporting this notion, expert performers report relatively little attention devoted to motor behavior. The 1984 Olympic medalist, Peter Vidmar, recalled that the majority of elements of his routine occurred automatically. Behavioral evidence also suggests that those who are experienced dedicate a smaller quantity of attention during performance compared to those with less experience. For example, skilled soccer players are able to maintain dribbling performance while also attending to a visual-monitoring task whereas the dribbling performance of less skilled players declined (Smith & Chamberlin, 1992). Beilock, Wierenga, and Carr (2002), using a golf putting task, observed that experience enabled performers to spare attentional processes associated with task execution such that resources were available for additional tasks. Furthermore, experts who allocate excess attentional resources toward a task incur a performance decrement (Beilock & Carr, 2002; Grey, 2004). The effect of expertise on attention is even

evident in tasks that require minimal attention such as postural control (Vuillerme & Nougier, 2004). Reductions in attentional demand as motor learning progresses are hypothesized to result from changes in the neural networks that underlie these behaviors.

Motor learning and neural efficiency.

From a neurobiological perspective the decrease in attentional demand as learning progresses may be caused by a streamlining of cortical/cognitive involvement. It is widely accepted that both cortical and subcortical brain regions are involved in motor learning (Greybiel, 1995). Specifically, the early stages of motor learning are characterized by prefrontal cortex activation and networking between frontal and parietal regions whereas later stages are hypothesized to have less cortical and more subcortical involvement (Flyer-lea & Matthews, 2004; Ghilardi, et al. 2000; Grafton et al. 2002; Kandel Schwartz & Jessell, 2000). The cerebral-cortical networking associated with motor execution becomes refined as one learns a task (Bell & Fox, 1996; Busk & Galbraith, 1975). Further support for these notions comes from Gentili et al. (2009) in which participants received visual feedback incongruent (60° rotation) with the actual location (proprioception) of their hand on the 2-D digitized surface while learning a novel visuomotor pointing task. As learning progressed the observed refinements in cortical networking were interpreted as underlying mechanisms for the improved performance recorded across the learning trajectory. In addition, neuroimaging studies of motor learning reveal decreases in specific cortical activation patterns (Haier et al., 1992, Kerick et al., 2004). A streamlining, or refinement, of cortical

processes during superior performance is implicated by these adaptations (see Hatfield et al., 2004 for a review). While neuroimaging evidence provides insights into changes in brain activity associated with motor learning, it does not directly address the attentional dynamics.

Possible link between neural efficiency and attentional processes.

The refinement in cortical dynamics associated with learning, such as those observed in the studies described above, may underlie reductions in attentional demand during skilled motor performance. In this regard, expertise results in reallocation of the neural resources associated with motor performance. Increases in the resources available to meet attentional demands would be a plausible outcome of this reallocation and should allow for broadened attentional focus beyond that associated with the primary motor task (Weissman, Roberts, Visscher, & Woldorff, 2006). However, the physiological processes associated with this shift have not been rigorously investigated. Behavioral (i.e., dual task) studies reveal changes in attention with learning, however, psychophysiological indices of attentional processes have not been employed for probing of attention across the dynamic process of motor learning. Such a psychophysiological level of analysis provides for objective measurement of underlying neural processes that mediate behavior. More specifically, EEG provides the temporal resolution necessary to reveal the dynamic relationship between attention and motor learning.

Psychophysiological investigation of cognitive workload and attentional reserve.

Psychophysiological methods have been successfully employed to assess cognitive workload (Humphrey & Kramer, 1994; Kerick, Hatfield, & Allender, 2007; Parasuraman, 1980; Senkowski & Herrmann, 2002). Specifically, components of the event related potential (ERP) have been used to infer changes in the amount of attentional resources consumed by a task. In order to obtain an objective index of attentional reserve as a function of workload, Allison and Polich (2008) challenged participants with a video game (first-person shooter) under different levels of difficulty (i.e., view, easy, and hard) while recording the cortical response to an auditory probe (modified oddball task). They observed a reduction in the ERP amplitudes in response to the tone as workload (game difficulty) increased; suggesting that as task difficulty increases the neural resources available to attend to incoming auditory stimuli decreases. Similarly, Miller, Rietschel, McDonald, and Hatfield (2011) incrementally varied the difficulty of a visuomotor task (Tetris®) by manipulating game speed, while probing attentional reserve using novel sounds as opposed to tones. They observed a dose-dependent reduction in ERP components during more difficult task conditions. In this regard, if the changes in cortical processes associated with motor learning ‘frees up’ the cortical resources demanded by attentional focus then changes in ERP amplitudes should reflect this. Thus, implementation of the modified oddball would provide an objective, direct method to test the proposed mechanism underlying changes in attentional allocation as a function of motor learning.

ERP components as a means to quantify attention.

It has been suggested that traditional dual task methods inherently confound primary task assessment due to competing responses (Kramer, Wickens & Donchin, 1985). However, confounds with the primary task are reduced when employing the modified oddball as no behavioral response is required. Specifically, relative to the standard oddball, the modified version replaces common tones with silence eliminating the need for the participant to engage in tone discrimination. The rare tone elicits both N1 and P2 components which are thought to reflect early perceptual processing resources and may be sensitive to attentional processes (Donchin et al., 1984; Kramer, Trejo, & Humphrey; Nagy et al., 2003; Peters et al., 2005; Picton and Hillyard, 1974; Ullsperger, Freude, & Erdmann, 2001). In accord, in the Miller & Rietschel et al. (2011) study, as game speed increased there was a concomitant reduction in both the N1 and P2 associated with the auditory probe. This suggests that increasing levels of task difficulty impose greater demand on early sensory processes. Additionally, Miller & Rietschel et al. replaced tones with novel sounds to increase the ecological validity while measuring the allocation of attention. These novel sounds induce the novelty P3 and LPP components in addition to the N1 and P2 (Miller & Rietschel et al.; Ullsperger, Freude, & Erdmann). The novelty P3 is thought to reflect the spare central processes available for reflexive orienting of attention and its topography is maximal frontally (rather than parietally as in the case of the P3b) (Friedman et al., 2001; McDonald et al., 2010; SanMiguel et al., 2010; Ullsperger, Freude, & Erdmann), whereas, the LPP has been reputed to index non

obligatory cognitive evaluation of stimuli (Ruchkin et al. 1988). Accordingly, Miller & Rietschel et al. observed an inverse relationship between amplitude of both the novelty P3 as well as the LPP with task difficulty suggesting less attentional reserve and reduced ability to evaluate the sounds. Thus, given the relationship between these components (particularly the novelty P3) and their cognitive interpretation (construct of attentional reserve), they are well suited to be employed as dependent measures in this study.

Statement of the problem and hypotheses.

It is clear that attentional processes change while learning a motor task and that the streamlining of activation in areas associated with task execution is an integral component. However, direct physiological support is lacking. **Thus, the purpose of this study is to provide neurobiological evidence of the positive relationship between motor skill and attentional reserve.** In this regard, half the participants will learn a novel visuomotor distortion task (learning group) and half the participants will perform the same task with no distortion (control group). Visuomotor adaptation can serve as a model of motor skill acquisition (see Krakauer, 2009 for review). Neurophysiological correlates of attentional capacity (i.e., brain electrical activity) will be monitored throughout task production in both groups. Specifically, we predict an interactive effect between group and time with regards to attentional reserve as indexed by components of the derived ERP. Such that, the amplitudes of N1, P2, novelty P3, and the LPP will be initially attenuated in the learning group relative to that of the control group and will

progressively increase in amplitude, whereas these amplitudes will be relatively stable in the control group.

Methods

Participants.

Participants included 26 individuals, however five were excluded due to excessive EEG artifact resulting in a final sample of 21 (9 women, mean age of 25 (2.70), ranged 21-30). All participants reported being free of neurological disorders and hearing impairment as determined by a health status questionnaire (HSQ) (Appendix 1). Additionally, all participants were right-handed as determined by the Edinburgh handedness inventory (EHI) (Appendix 2). Finally, all participants provided informed consent (Appendix 3) on a form approved by the University of Maryland Institutional Review Board and were compensated \$60 for being enrolled in the study.

Participants were randomly assigned to one of two groups, control ($n = 10$) or learning ($n = 11$), described below. An independent t-test confirmed that the two groups did not differ with regard to age, $p > .05$.

Instrumentation.

Experimental setup. For a pictorial description of the experimental setup see figure 1. Additionally, a schematic is provided in Appendix 4 that illustrates how the individual pieces of equipment were interfaced. Participants were seated in front of a visuomotor research apparatus (Wang & Sainburg, 2005) with both their hands on a horizontal surface directly in front of them. There was a horizontal mirror 13" above the surface upon which their hands were placed that occluded hand position from the participants' view. Additionally, the mirror

displayed
the visual
stimuli
associated
with the
visuomotor
distortion
task (i.e.,
start circle,
target, and



Figure 1: A pictorial description of the task

cursor representing hand position). The mirror reflected images displayed on 50” LCD television (Panasonic) which was suspended above the mirror. Thus, visual stimuli were displayed on the television and the reflection was viewed by the participants on the mirror while their hand location was blocked from their visual field. Therefore, the visual feedback available to the participants regarding their movements was limited to the display on the mirror.

The participants’ non-dominant hand (left) was placed in an adjustable brace that immobilizes all joint movement distal to the elbow. This brace was supported over the horizontal surface by an air-jet system, which reduced the effects of friction and gravity. A single sensor was fixed to the air sled to record hand location. Location was sampled using a Flock of Birds (FoB)[®] (Ascension-Technology) magnetic six-degree-of-freedom (6-DOF) movement recording system. As the horizontal surface defined the X-Y plane, perpendicular axis

displacement was constant. Thus, using the recorded X-Y coordinates of hand location, we were able to project a cursor on the screen. Screen redrawing occurred quickly enough to maintain perception of the cursor and hand location as consistent with 'real time'. Data were collected with a sampling rate of 130 Hz using a Macintosh computer, which was used to record sensor location via serial ports. The participants' dominant hand (right) was placed on the horizontal surface beneath the mirror in a comfortable resting position.

Participants were fitted with a stretchable EEG cap that housed a 64 channel BrainVision atciCAP system (Brain Products, Munich, Germany). Their chin was placed in a comfortable brace, and their head rested against a padded forehead restraint to limit movements. Auditory stimuli were delivered via silicone tubes to binaurally inserted audiometric quality ear-phones (Neuroscan, El Paso, Texas).

Visuomotor task demands. The task consisted of a series of center-out reaching movements with the non-dominant (left) hand. During non-dominant hand motor learning widespread frontal and temporal regions are recruited (Grafton, Hazeltine, & Ivry, 2002). This strategy was employed to consume more time and attentional resources relative to the dominant hand, increasing the ability to detect changes in attentional processes as learning progressed. For each trial, the participant was presented with a green 'home' circle that was 2.5 cm in diameter and located in the center of the left visual field. The participant also saw a cursor on the screen which corresponded to the current location of the sensor placed on their left hand. Additionally, one of the eight possible target circles was

displayed in grey with a 2.5 cm diameter. Targets were located 18 cm from the home circle radially and equally spaced apart, see figure 2. The participant was instructed to wait in the home circle for at least 2 seconds and then were to move as quickly and accurately (straight line) to the target that is currently displayed. Each trial lasted a total of six seconds (2 seconds prior to movement onset and an additional 4 seconds after movement onset). If the target was reached before 4 seconds had elapsed the participant remained inside the target circle for the remaining duration of the trial. At the end of the 6 seconds, the movement path was displayed for 2 seconds and then the target circle and movement path disappeared. Finally, the next target was displayed and the participant returned to the home circle to begin the next trial.

There were two types of trials: 1-visually congruent (no rotation) and 2-visually distorted (rotation). For the no rotation trials the cursor was veridical with the movement of the left hand. However, the rotation trials consisted of a 60° counter-clockwise rotation, such that for a given trajectory, participants observed their cursor moving 60° distorted from their actual movement (figure 2). The targets were in the same location regardless of trial type (i.e. the distortion was applied only to the cursor location during movement). Thus, exposure to the rotation trials will require participants to compensate for the visual distortion in order to successfully perform the motor task.

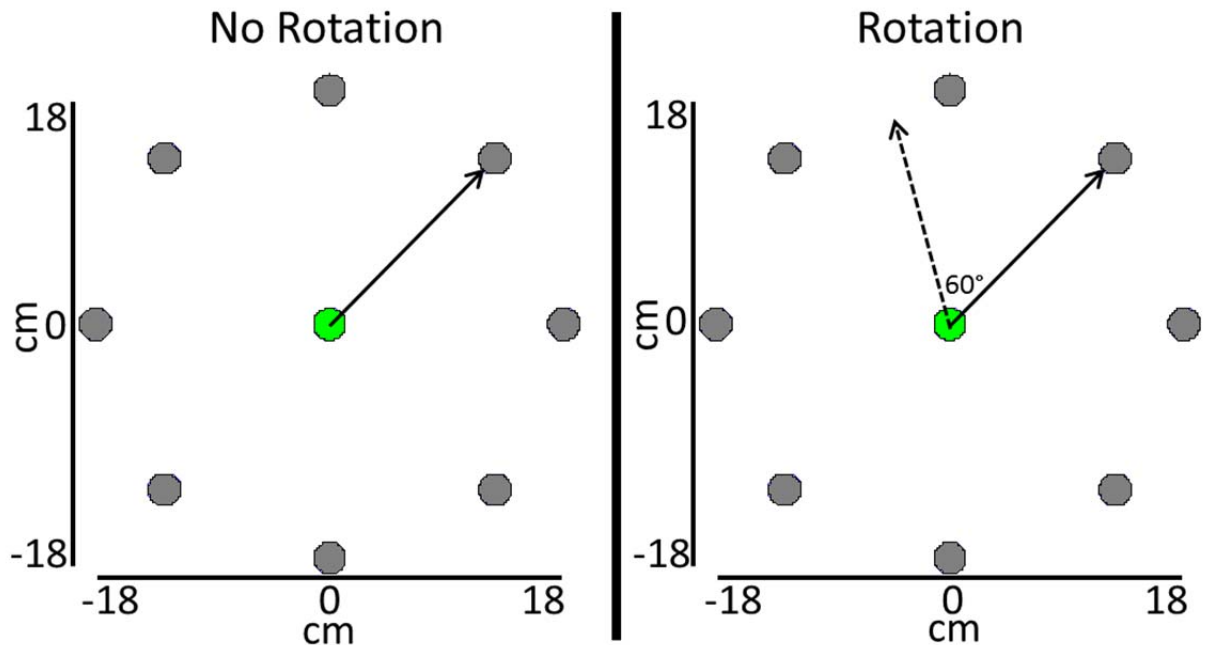


Figure 2: Task description with the left panel illustrating an optimal trajectory of a no rotation (congruent) and the visual feedback . On the right, a rotation trial (incongruent) is shown with the same motor behavior (solid line) along with the visual feedback a participant would have observed for that behavior (dotted line). Note: for a given trial only one target will be displayed at a time.

Auditory probe. A variant of the traditional oddball task was used to probe attentional reserve where the common tones are replaced with silence and the rare tones are replaced with novel sounds (ex. dog bark). This paradigm elicits many of the same ERP components as the traditional oddball (Polich & Margala, 1997) even when ignored (Mertens & Polich, 1997), while being more robust to any habituation effects associated with repetitious stimuli (Wetter et al., 2004). This variant of the oddball allows simultaneous probing of attentional reserve and cognitive-motor learning without interfering with primary task execution, in this case learning a novel visuo-motor task.

Novel sounds were employed rather than a single tone stimulus in order to elicit the novelty P3 component as the novelty P3 has been demonstrated to index

the involuntary reflex of attention (McDonald et al., 2009; Ullsperger, Freude, & Erdmann, 2001). As such, 30 stimuli were randomly selected from a larger set of 96 sounds obtained from the New York State Psychiatric Institute (Fabiani et al., 1996). Sound presentation was controlled using LabVIEW 8.5 software running on a PC (Dell Dimension DM-5150, Round Rock, Texas), and generated using a sound card (SigmaTel STAC 92XX C-Major HD, Austin, Texas), presented binaurally, as described above, at 85 dB SPL.

Psychophysiological Recordings. Electroencephalographic data were collected using an actiCAP EEG system (Brain Products GmbH, Munich, Germany) and were acquired from 64-sites (dense-electrode array was used for additional analyses outside the scope of dissertation work), labeled in accordance with an extended 10-20 international system (Jasper, 1958). The EEG data were online referenced to the right earlobe and a common ground was employed at the FPz site. Electrode impedances were maintained below 10 k Ω throughout the experiment and bandpass filters were set at .01-100 Hz with a sampling rate of 1 kHz. The EEG signal was amplified and digitized using a BrainAmp DC amplifier (Brain Products GmbH, Munich, Germany) linked to Brain Vision Recorder software version 1.10 (Brain Products GmbH, Munich, Germany) running on a Gateway laptop (Model MC7833U, Irvine, California)

Procedures.

Upon entering the lab participants completed the informed consent, HSQ and EHI. Then participants were fitted with the EEG cap and conducting gel (SuperVisc-Gel®, EasyCap, Herrsching, Germany) was applied. Next,

participants were seated in front of the visuomotor apparatus; their left hand was placed in the air-jet brace and the ear buds were placed in the participant's ears. Participants were then given 56 practice trials to become familiar with the apparatus and were presented with approximately 10 sounds to ensure the volume was tolerable. Finally, when all electrode impedances reached acceptable levels ($< 10 \text{ k}\Omega$) data acquisition began.

The experimental protocol consisted of seven blocks of 56 trials each of the visuomotor task with each target appearing an equal number of times in each block (i.e., seven). The first block consisted of all visually congruent trials for both the control and learning groups. The two groups were treated differently during the next five blocks. Specifically, the learning group was presented with all incongruent trials, such that they had to adapt to the distortion in order to navigate the task whereas the control group continued to be presented with congruent trials during these blocks. Finally, during block 7 the learning group was exposed to congruent trials and the control group was presented with incongruent trials.

Throughout all blocks, participants were intermittently probed with the auditory stimuli. Specifically, the auditory probes occurred between 50 – 950 ms after movement onset with a random interstimulus interval and had a 45% chance of being presented on any given trial. These parameters were in place to increase the novelty of the sound presentation while increasing the likelihood that the participants were actively engaged in the reaching task (i.e. not waiting for the next trial to begin). Participants were instructed to prioritize performance of the visuomotor task and were explicitly told to move as quickly and accurately to the

target circles after waiting in the home circle for at least two seconds. A visual cue was given to return to the home circle and the trial was restarted if the participant left the home circle prior to waiting 2 seconds. Participants were told that the sounds were irrelevant to the task and there was no objective with regard to the sounds.

Data Processing.

Kinematic data from the visuomotor task were processed using in-house software (Appendix 5) written in the Matlab environment (MATLAB 7.4, Natick, MA). All Cartesian position data were dual low-pass filtered at 8 Hz using a third-order butterworth filter. Initial directional error (IDE) was computed (measured in degrees) as the difference between the direction of the target from the center of the home circle and the direction of the sensor place on the hand at peak outward velocity from the center of the home circle. For each block, IDE values were computed for the first two trials to each of the eight targets (i.e. 16 trials per block) and then averaged. IDE serves as an index of movement planning as it is calculated prior to any error correction due to visual feedback of the movement (Krakauer et al, 2000).

All signal processing of the EEG data were conducted using BrainVision Analyzer software version 2.0 (Brain Products GmbH, Munich, Germany). Continuous data consisting of all seven experimental blocks were referenced to an averaged ears montage and then low-pass filtered at 20 Hz with a 48-dB rolloff using a zero phase butterworth filter. The data were then spline fit to 250 Hz and epoched into 4-second sweeps (\pm two seconds around movement onset). Next, all

sweeps were visually inspected and trials containing non-stereotyped artifacts were excluded from further analyses, a technique referred to as pruning, which improves the ability of an independent component analysis to identify stable components (Onton et al., 2006). Eye movement artifact was reduced using the ICA-based ocular artifact rejection function within the Brain Vision Analyzer software, electrode FP2 served as the VEOG channel and electrodes AF7 and AF8 served as the bipolar HEOG channel. The VEOG algorithm searches for an eyeblink template in channel FP2 and then finds ICA-derived components that account for a user specified (70%) amount of variance in the template matched portion of the signal from FP2. The HEOG algorithm finds ICA-derived components that account for a user specified (30%) amount of variance in the entire signal from the HEOG channel (bipolar-AF7 & AF8). These components were removed from the raw EEG signal and the recording reconstructed for further processing.

The data were then sorted by block and epoched into 1-second sweeps around presentation of the auditory stimuli (-100 to 900 ms). The data were baseline corrected using the mean of the prestimulus interval and then were visually inspected to remove any remaining trials that contained artifact. For each subject and block, the remaining trials were averaged and none of these averages were derived using less than 20 trials, mean number of trials = 23.32 (2.89).

The temporal windows from which the average amplitude for each of the four components was determined by a grand average, see figure 3 (i.e. collapsing across all subjects and blocks). Next, for each component the latency at peak

amplitude was identified and a window around the peak amplitude was determined, an approach suggested by Handy (2005) and Luck (2005). Average amplitude was calculated for each of the four components and current source densities were computed. These were projected on the scalp to confirm the windows corresponding to each component exhibited a topographical distribution consistent with how each component has been described in the extant literature, see figure 3. The resultant windows were: N1 = 100 – 120 ms, P2 = 170 – 210, novelty P3 = 250 – 290 ms, and LPP = 500 – 700 ms. Finally, average amplitudes were computed for each subject and block using these windows at the midlines electrode sites, Fz, Cz, and Pz.

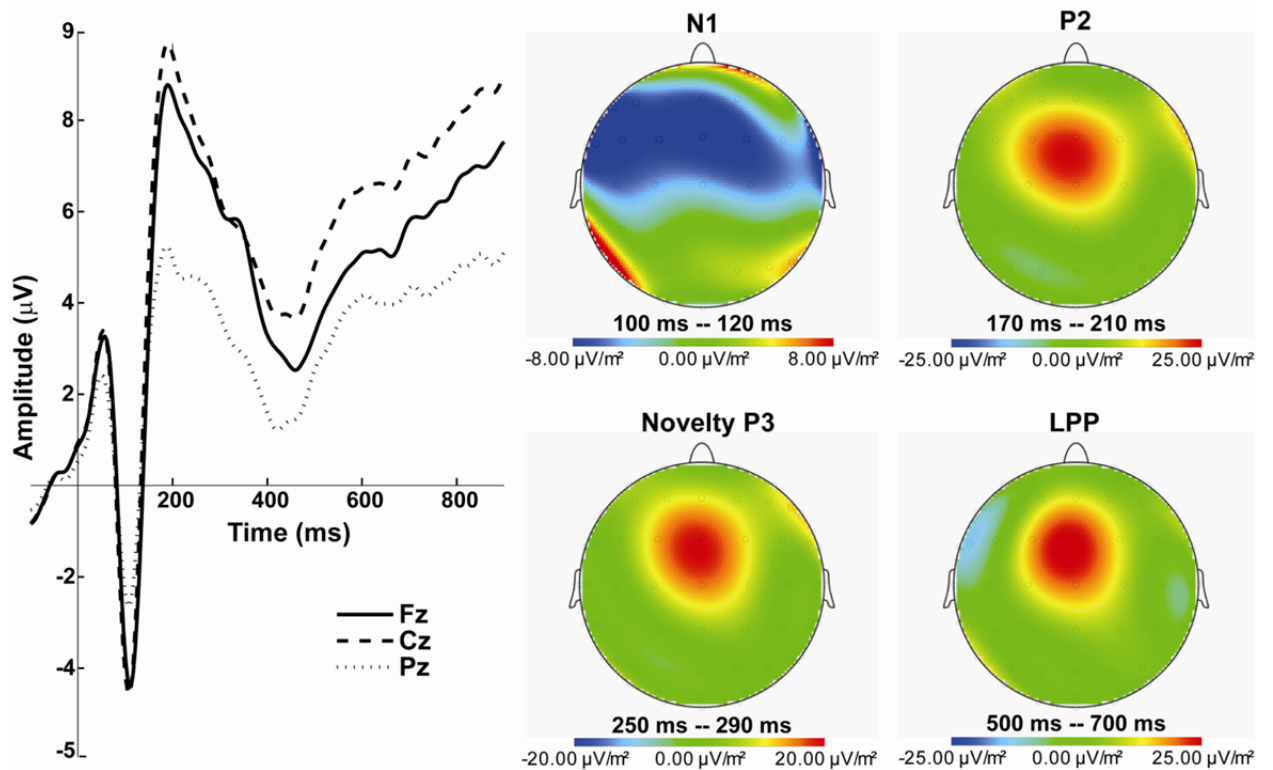


Figure 3: On the left are the grand averaged ERPs collapsed across both groups and all blocks. Each line corresponds to a different midline electrode site, Fz, Cz, and Pz. On the right are the current source density plots for each of the four ERP components projected onto the scalp topography.

Statistical Analysis.

The kinematic variable IDE was subjected to a 2 (Group) X 5 (Block) ANOVA, see figure 4. Specifically, the blocks used in the analysis were block 1 (prior to distortion in the learning group), blocks 2, 4, & 6, which were used to characterize early, middle, and late learning, respectively, and block 7 (learning group receiving veridical feedback again and the control group receiving distorted feedback for the first time). Similarly, each of the four ERP component average amplitudes was subjected to separate 2 (Group) X 5 (Block) ANOVAs with the additional of the factor Region (Fz, Cz, and Pz). Thus, four 3-factor ANOVAs were computed for the ERP components.

Conventional degrees of freedom are reported, and the Huynh-Feldt correction was provided when sphericity was violated. The p-values reported were based upon the corrected degrees of freedom and Cohen's *d* effect sizes are provided when appropriate. Post hoc procedures are described in the results section.

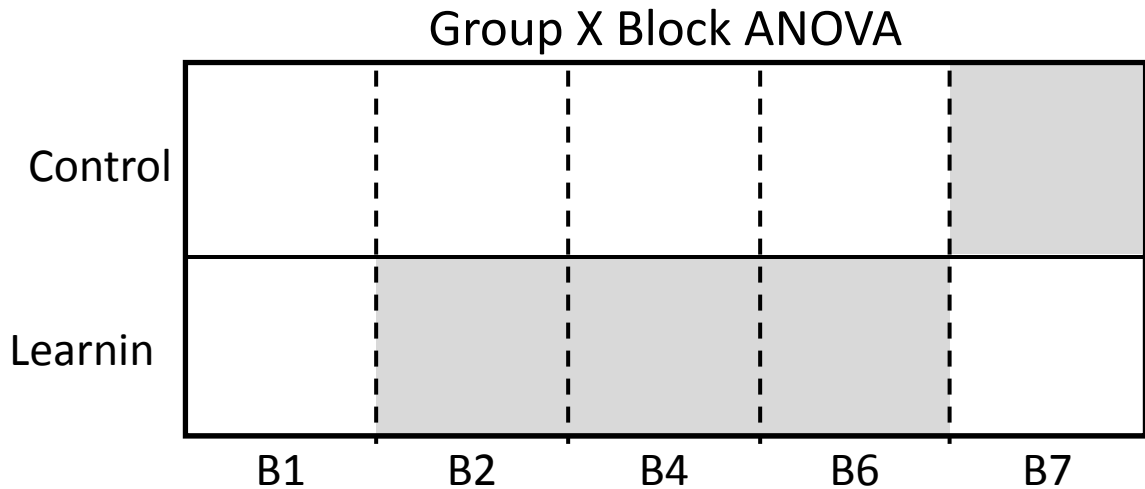


Figure 4: Represents the statistical design for IDE with the shaded regions representing blocks where the trials were rotated (incongruent). The statistical design for each of the ERP components was similar with the only difference being the addition of the factor region (Fz, Cz, and Pz)

Results

Kinematic Analysis.

The statistical analysis examining IDE revealed a significant Group X Block interaction ($F(4,76) = 453.93, p < .001, \epsilon = .65$). To determine the effect of Group for each block, a series of five independent t-tests were employed. If Levene's Test for equality of variances was significant the t-statistic and corresponding p-value associated with *equal variance not assumed* was reported, however, conventional degrees of freedom were provided. These analyses revealed that the groups were undifferentiated during block 1. The learning group exhibited a significant increase (in the negative direction) in IDE during block 2 ($t(19) = 24.10, p < .001, d = 10.07$), block 4 ($t(19) = 6.45, p < .001, d = 2.69$), and block 6 ($t(19) = 6.18, p < .001, d = 2.59$) relative to the control group. Additionally, the learning group exhibited significantly greater IDE (in the positive direction) during block 7 ($t(19) = 23.78, p < .001, d = 10.17$) relative to the control group. See left side of figure 5.

To determine the dynamics of IDE across the blocks for each group separate one-way ANOVAs were computed for each group for the factor Block. The ANOVA for the control group was significant ($F(4,36) = 663.81, p < .001, \epsilon = .43$). Post hoc analyses were performed using Tukey's HSD and revealed that IDE was significantly greater (in the negative direction) during block 7 relative to all other blocks ($p < .01$) with the following effect sizes: $d = 12.26, 13.41, 12.76$, and 12.17 for blocks 1, 2, 4, and 6, respectively. Whereas all other blocks were undifferentiated, see right side of figure 5. In addition, the ANOVA for the

learning group was also significant ($F(4,40) = 200.22, p < .001, \epsilon = .64$). Tukey's HSD post hoc analysis revealed multiple significant findings for IDE in the learning group, thus for clarity, only comparison of sequential blocks are reported. Specifically, that IDE was significantly greater (in the negative direction) during block 2 as compared to block 1 ($p < .01, d = 10.61$). IDE became significantly reduced (closer to 0) during block 4 relative to block 2 ($p < .01, d = 4.03$), but was not statistically different between blocks 4 and 6. Finally, IDE was significantly greater (in the positive direction) during block 7 relative to block 6 ($p < .01, d = 5.42$), see right side of figure 5. For all possible IDE comparisons with regard to block for each of the two groups with corresponding effect sizes, please see Appendix 6.

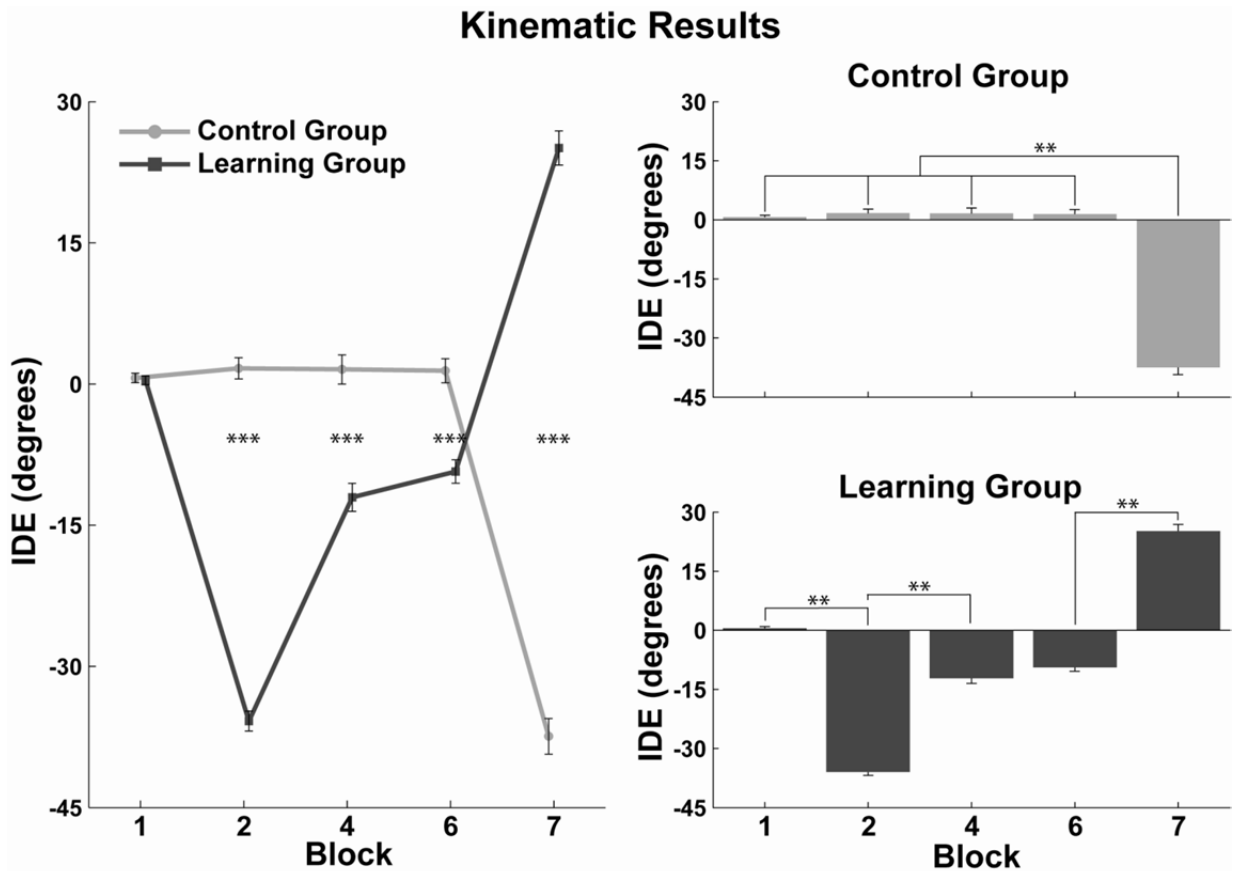


Figure 5: IDE results. The left panel corresponds to the comparison of the two groups (control and learning) within each block. The right panel compares how IDE changes between sequential blocks for each of two groups separately, **p < .01, *p < .001.**

ERP Analyses.

The grand averaged ERPs separated by group and block are provided in figure 6.

N1 component. No significance was observed with regard to Block and Group for the N1 component.

P2 component. No significance was observed with regard to Block and Group for the P2 component.

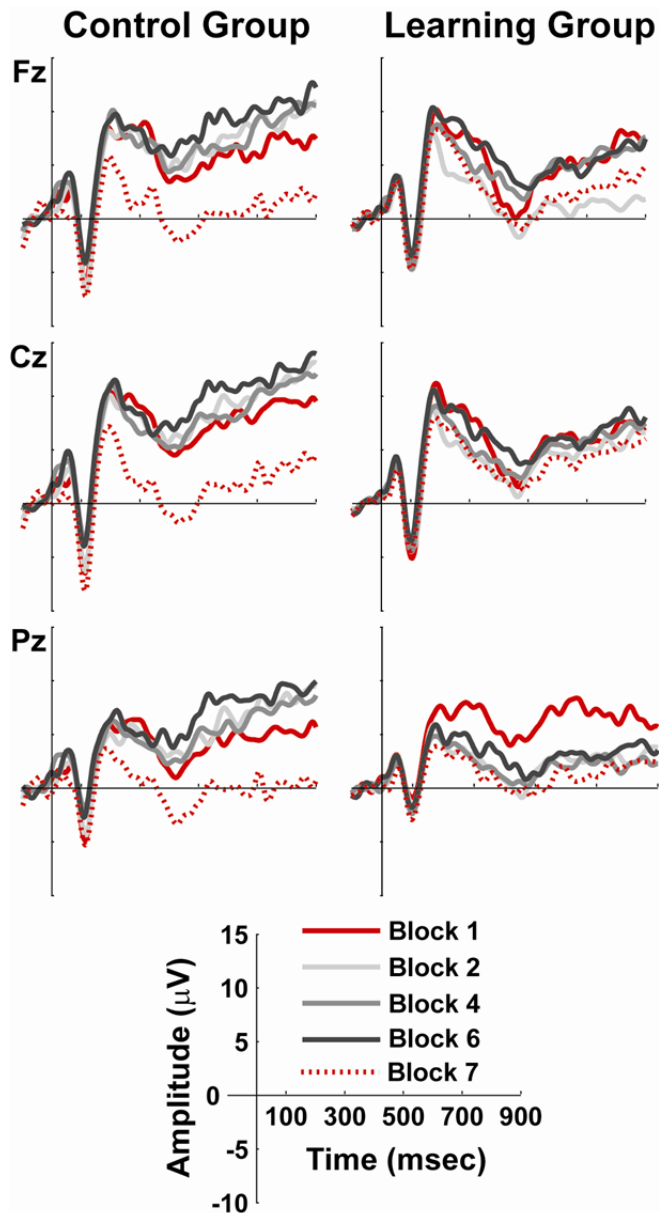


Figure 6: Grand average ERPs separated by group and block.

revealed that the groups were undifferentiated during block 1. However, during block 2, the learning group exhibited a significant reduction in novelty P3 amplitude as compared to the control group ($t(19) = 2.18, p < .05, d = 0.95$). The groups were undifferentiated during the remaining three blocks, see left side of Figure 7.

Novelty P3

component. The Group X Block X Region ANOVA revealed a significant 3-way interaction ($F(8,152) = 2.29, p = .05, \epsilon = .59$). To determine the nature of this interaction, 3-separate Group X Block ANOVAs were conducted for each region.

For the Fz region, there was a significant Block X Group interaction ($F(4,76) = 6.47, p < .001, \epsilon = .92$). To determine the effect of Group for each block a series of five independent t-tests were employed. These analyses

To determine the dynamics of novelty P3 (at the Fz region) across the blocks for each Group separate one-way ANOVAs were computed for each group for the factor Block. The ANOVA for the control group was significant ($F(4,36) = 9.71, p < .001$). Post hoc analyses performed using Tukey's HSD revealed that novelty P3 was significantly reduced during block 7 relative to all other blocks ($p < .01$) with the following effect sizes: $d = 1.56, 1.58, 1.64, 1.86$ for blocks 1, 2, 4, and 6, respectively. Whereas all other block comparisons were undifferentiated, see right side of figure 6. In addition, the ANOVA for the learning group was also significant ($F(4,40) = 6.82, p < .001, \epsilon = .89$). Tukey's HSD post hoc analysis revealed that the novelty P3 became significantly reduced during block 2 as compared to block 1 ($p < .01, d = 0.71$). The novelty P3 was significantly greater in block 6 as compared to block 2 ($p < .01, d = 0.97$). Finally, the novelty P3 was, again, significantly reduced during block 7 as compared to block 6 ($p < .05, d = 0.54$), see right side of figure 7.

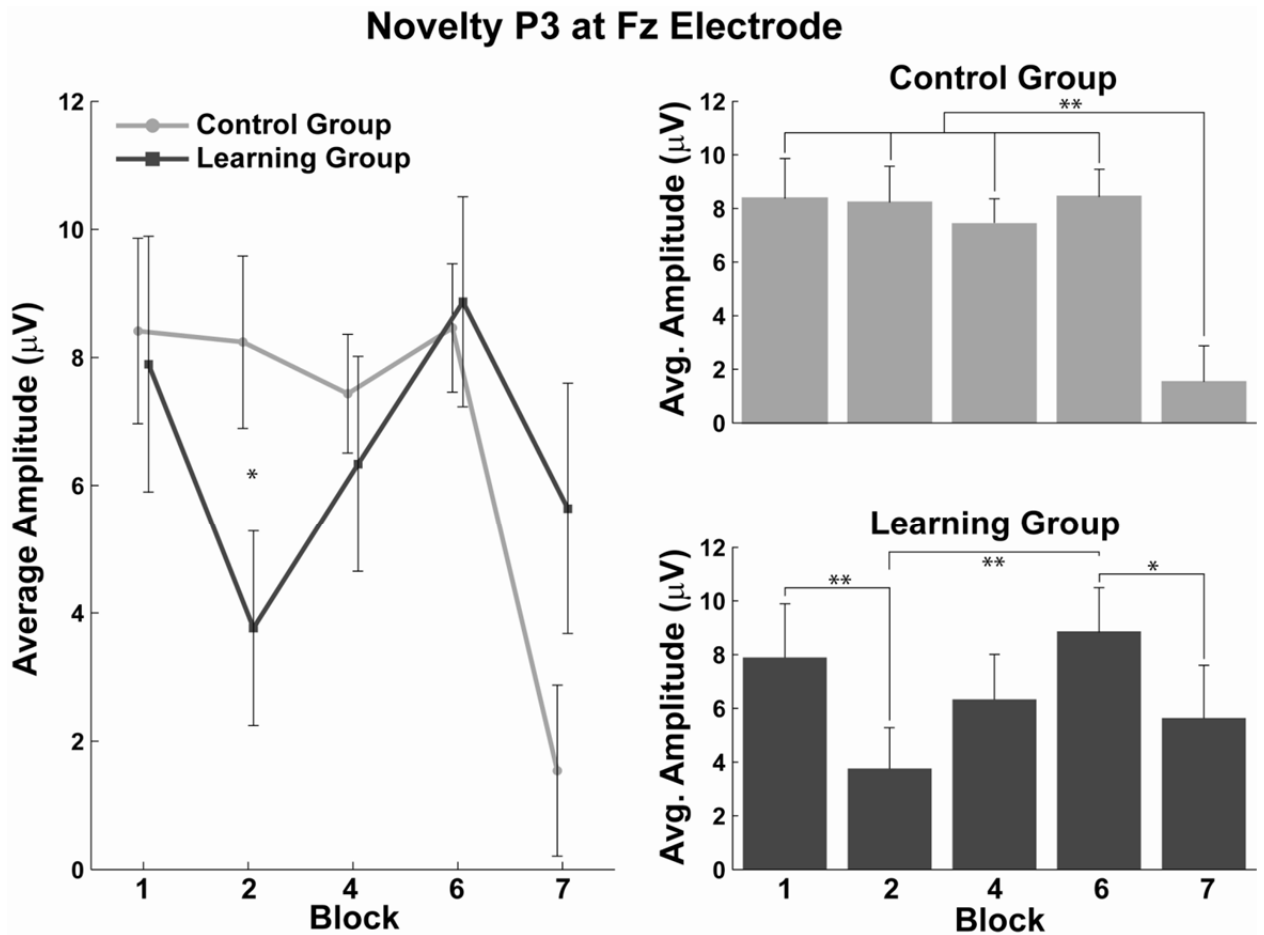


Figure 7: Novelty P3 results at the Fz electrode. The left panel corresponds to the comparison of the two groups (control and learning) within each block. The right panel displays the block comparison for each of the two groups separately, * $p < .05$, ** $p < .01$.

For the Cz electrode, there was a significant Block X Group interaction ($F(4,76) = 3.63, p < .01, \epsilon = .92$). To determine the effect of Group for each block a series of five independent t-tests were employed, however none of these comparisons were significant.

To determine the dynamics of novelty P3 (at the Cz region) across the blocks for each group separate one-way ANOVAs were computed for each group for the factor Block. The ANOVA for the control group was significant ($F(4,36) = 5.92, p < .001$). Post hoc analyses were performed using Tukey's HSD and revealed that novelty P3 was significantly reduced during block 7 relative to all

other blocks: block 1 ($p < .01$, $d = 1.45$), block 2 ($p < .01$, $d = 1.14$), block 4 ($p < .05$, $d = 1.13$) and block 6 ($p < .01$, $d = 1.43$), see figure 8. In addition, the ANOVA for the learning group was also significant ($F(4,40) = 5.91$, $p < .001$). Tukey's HSD post hoc analysis revealed that the novelty P3 became significantly reduced during block 2 as compared to block 1 ($p < .01$, $d = 0.90$). The novelty P3 during block 4 was not significantly greater as compared to block 2 ($p > .05$), but was also significantly reduced as compared to block 1 ($p < .05$, $d = 0.56$). In addition, the novelty P3 was significantly greater in block 6 as compared to block 2 ($p < .05$, $d = 0.82$). Finally, the novelty P3 during block 7 was significantly reduced as compared to block 1 ($p < .05$, $d = 0.65$), see figure 8.

The Group X Block ANOVA for the Pz electrode yielded no significance.

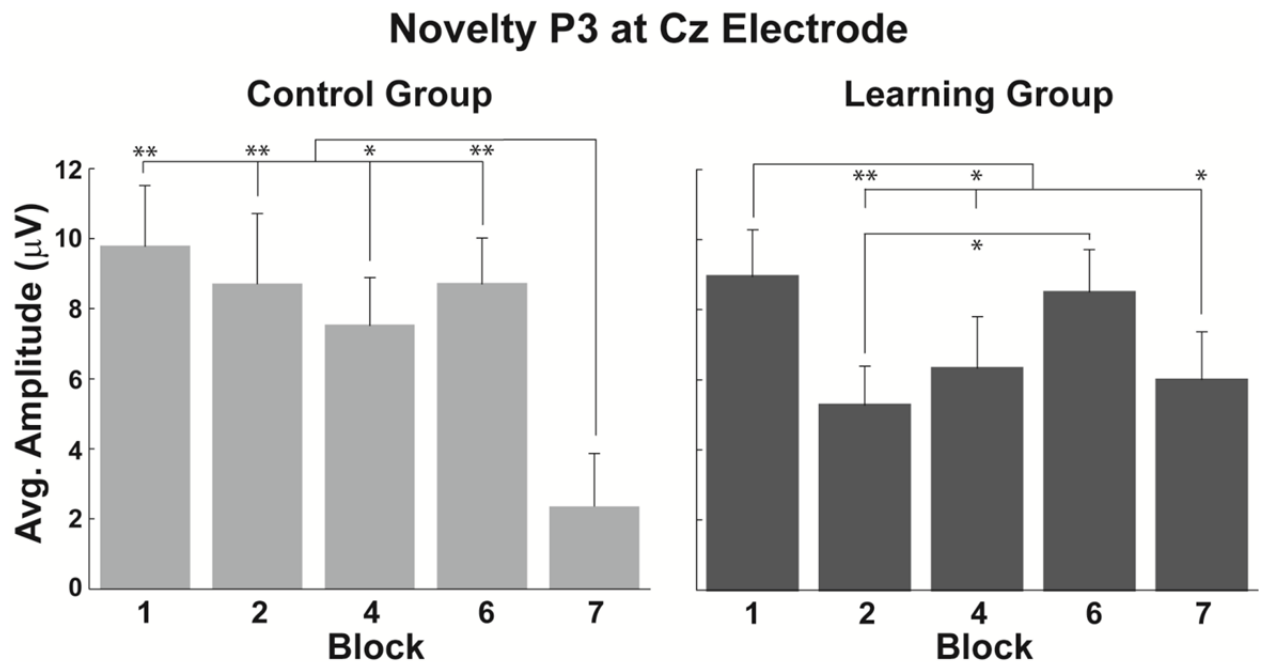


Figure 8: Novelty P3 results at the Cz electrode. Each plot displays the block comparison; control on the left, and learning on the right, * $p < .05$, ** $p < .01$.

LPP component. The Group X Block X Region ANOVA revealed a significant 2-way interaction involving Group and Block ($F(4,76) = 3.303$, $p <$

.05). Tukey's HSD post hoc analysis revealed that for each of the five blocks the LPP was undifferentiated between the control and learning groups. Further, for the learning group, there were no differences observed between any of the 5 blocks. However, for the control group differences with regard to the LPP were observed between the blocks. Specifically, the LPP was significantly reduced during block 7 as compared to block 2 ($p < .01$, $d = 0.92$, block 4 ($p < .01$, $d = 1.21$), and block 6 ($p < .01$, $d = 1.31$), see figure 9.

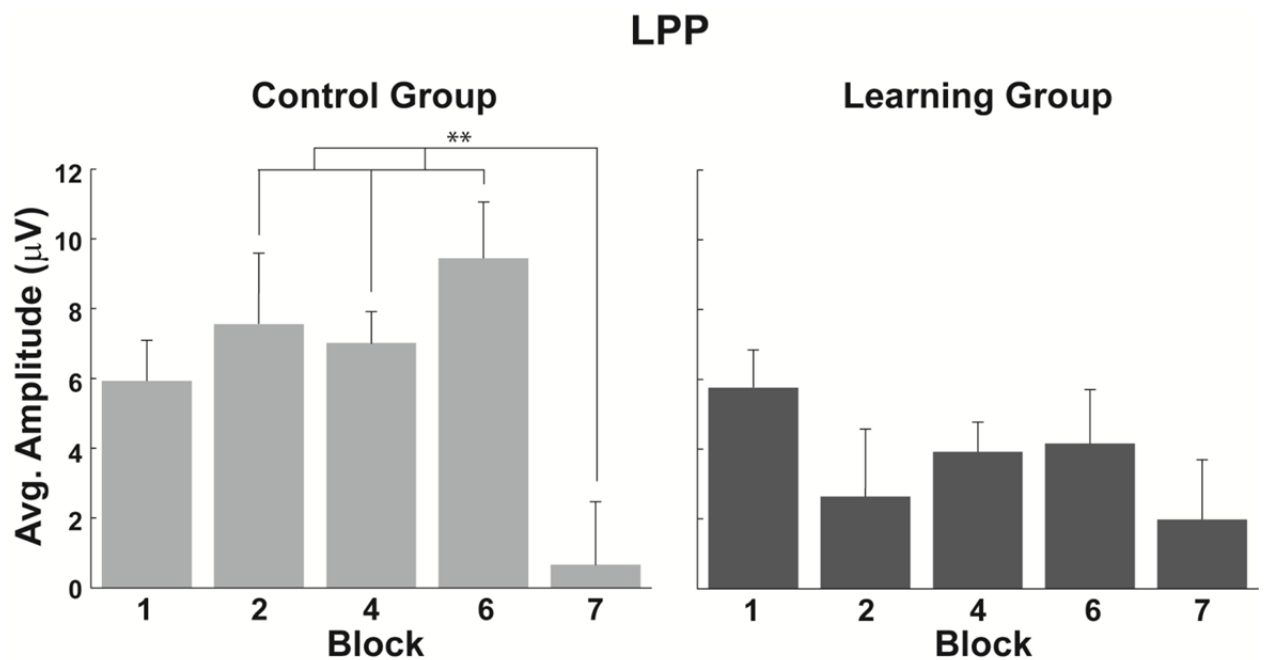


Figure 9: LPP results across the collapsed across three midline regions. Each plot displays the block comparison; control on the left, and learning on the right, ** $p < .01$.

Discussion

The aims of this study were to provide neurobiological evidence that attentional reserve increases as a function of motor learning and to further refine an electrophysiological index of attentional reserve. Accordingly, the pattern of IDE results in the learning group, particularly the positive values observed after the rotation was removed, suggests that a successful model of motor learning was achieved. Moreover, these increases in task competency were accompanied by changes in attentional processes as indexed by the novelty P3 amplitude. The increased attentional demands of early learning were reflected by reduced novelty P3 amplitude. However, as learning progressed, the attentional burden imposed by the task decreased, thus allowing more resources to become available to process the novel sounds (i.e. increased novelty P3 amplitudes). These findings, in concert with the similar pattern of novelty P3 results revealed in the Miller & Rietschel et al., 2011 study, provide objective psychophysiological support for the construct that attentional reserve increases as a function of skill level and, accordingly, across the course of motor learning.

The observed pattern of IDE results suggests the visuomotor distortion successfully served as a relevant model for motor learning (Krakauer, 2009). Importantly, the two groups did not significantly differ during block 1 in which both groups received veridical feedback. With the initial exposure to the rotation (block 2) the learning group exhibited an increase in IDE as compared to block 1 (no rotation) and as compared to the control group's block 2. This significantly reduced performance (as a consequence of the rotation) allowed for observation

of the participants' adaptation to the distortion and enabled the current study's model of motor learning. As the adaptation progressed the learning group reduced their IDE between blocks 2 and 4 and appeared to stabilize between blocks 4 and 6 (undifferentiated) although the corresponding IDE did not reduce to the level observed at baseline. Most importantly, there was a significant increase in IDE during block 7 (the visuomotor distortion was removed) as compared to block 6, and as predicted, IDE was in the opposite direction of those observed during the rotation. This phenomenon is commonly referred to as the after effect and provides evidence to support the occurrence of a motor adaptation in response to the distortion (Krakauer). Finally, the control group's performance was stable across blocks 1 through 6. As expected with the introduction of the rotation (block 7) they performed similarly to the learning group during their initial exposure to the distortion (block 2). In tandem, results from both the control and the learning group support employment of this distortion (see Methods) for necessitating a motor adaptation to accomplish the performance goals as described to the participants of this study. The pattern of adaptation observed by the learning group across the blocks and relative to the control group suggests that observation of changes in ERP components throughout the cognitive-motor challenge would provide insight into the dynamics of attentional processes as a function of motor learning.

Contrary to prediction, no significant differences were observed with regard to group or block for either the N1 or P2 components. However these predictions were based on the results of the Miller & Rietschel et al. 2011 study in

which task difficulty was manipulated. Specifically, changes in task difficulty were achieved by increasing the game speed, thus increasing the density of visual stimuli/unit time imposing greater demand on the early sensory processes. In accord, there was a significant reduction in both the N1 and P2 components amplitude as a function of task difficulty indicating reduced spare early sensory processing resources. However, in the current study the amount (density) of sensory information was held constant (psychometrically matched) across all groups and blocks, thus the stability of the N1 and P2 components follows logically. Moreover, the lack of differences observed in these earlier psychological constructs allows for a purer comparison of the variable of interest. Specifically, differences observed in attentional processes cannot be attributed to complexity of the visual environment, but rather task competency. Additionally, as these are exogenous components, which can be used to index the depth of sensory processing, one can infer comparable detection across the conditions. Thus, the dynamic change observed in the processing of the sounds is dependent on endogenous attentional processes and cognitive interpretation of the sounds.

The component identified as the novelty P3 exhibited a topography (frontal-central) and peak latency consistent with that described in the extant literature (see Friedman et al. 2001 for review). As expected, the novelty P3 was significantly different between the two groups and changed as a function of learning the task. Additionally, the statistical differences were observed at electrode sites where the component topography was expressed maximally. Specifically, at the Fz electrode the novelty P3 was undifferentiated between the

two groups prior to the distortion (i.e. during block 1). Further and consistent with the IDE result, the novelty P3 became reduced in the learning group during block 2 relative to both the control group during block 2 and the learning group during block 1. This suggests that more cognitive resources were consumed during the initial learning with subsequently fewer attentional resources available to process the sounds. As the experimental group learned the task there was a concomitant increase in the amplitude of the novelty P3. Specifically, this component increased between blocks 2 and 4, and continued to increase from blocks 4 to 6; the difference between blocks 2 and 6 was highly significant. As predicted, this suggests a progressive decrease in attentional demand imposed by the primary task across the course of learning, consequently allowing more attentional resources to become available for processing the sounds.

Importantly, at block 6 the novelty P3 was undifferentiated from that observed prior to rotation. Moreover, when the visuomotor distortion was removed (block 7) the novelty P3, again, became significantly reduced. Notably, during block 7 the amplitude of the novelty P3 was similar to that of mid learning (i.e. block 4) suggesting that after learning the distortion, the re-introduction of veridical feedback imposed a greater demand on attentional processes than it did initially at baseline (block 1/no distortion). Additionally, and consistent with the IDE results, the novelty P3 in the control group was not significantly different between blocks 1-6 until the introduction of the distortion in block 7, in which there was a significant reduction in the novelty P3 amplitude. A similar pattern of results was observed at the Cz electrode, however the groups were not

significantly different from each other during any of the blocks. This might have been due to increased component overlap at this more posterior electrode location, thus blurring the contribution of the novelty P3 (i.e. frontal electrode locations allows for greater independence of the novelty P3 quantification from components that are expressed during the same time window). Collectively, the novelty P3 results suggest that the attentional burden imposed by a novel motor task became reduced as participants learned the task and this change was mediated by the neurobiological processes underlying this component.

Accordingly, as the dynamics of the novelty P3 were so closely coupled with the learning of the task, a post-hoc source analysis was conducted to estimate the neural generators of this component. Specifically, a low-resolution electromagnetic tomography (LORETA) analysis was computed as housed within BrainVision Analyzer software version 2.0 (Brain Products GmbH, Munich, Germany), LORETA is a computational method for characterizing multiple sources within the EEG signal, see figure 10 (Pascual-Marquis et al., 1999). Consistent with Volpe et al. (2007), who also applied LORETA to the novelty P3 component, the neural generators were located in frontal-parietal and anterior cingulate regions. These areas are believed to comprise the cerebral network for the orienting of attention (Mesulam et al., 1990). As the increases in the amplitude of the novelty P3 component likely reflect greater activation of this network, the results of this study suggest that attentional orienting to novel events is enhanced as one becomes more proficient at a new motor skill. Additionally, electrophysiological and hemodynamic investigation during presentation of novel

sounds, rather than tones, revealed temporal lobe activation as well as frontal-parietal network activity (Opitz et al., 1999). Similarly, the current study employed novel sounds and temporal lobe sources of the novelty P3 were computed. As such, given the functions associated with these regions, the present results indicate greater conceptual and semantic processing of novel events as task competency improves.

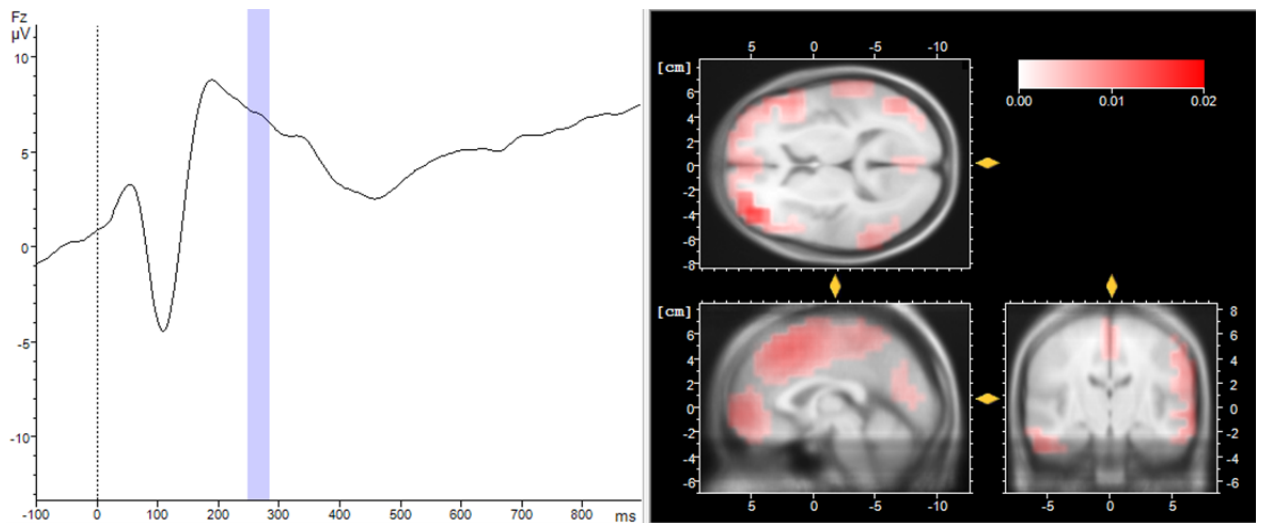


Figure 10: LORETA results for the novelty P3 window. On the left panel the novelty window is represented by the shaded region superimposed on the grand averaged ERP at the Fz electrode. On the right, are the LORETA source solutions.

The pattern of novelty P3 amplitude across the blocks for both groups, in conjunction with the functional neuroanatomy of the sources of the novelty P3, suggests that novel tasks impose a physiologically observable burden on attentional processes. Importantly, this increased cost or burden is reduced across the course of cognitive-motor learning, thus ‘freeing up’ attentional resources to cope with additional, novel stimuli. However, these findings could also be interpreted as an increased ability to shift the locus of attentional resources as motor learning progresses. For example, Bellenkes, Wickens, and Kramer (1997)

concluded that expert pilots were more flexible with regard to visual attention of flight instruments relative to novices. Thus, rather than a reduction in the attentional ‘cost’ associated with learning a task, it may be that one develops task-specific attentional flexibility where they are able to more quickly redirect attentional resources from the task to a novel event and then back to the task.

While the current study does not provide evidence in favor of either interpretation, the initial interpretation is parsimonious. Regardless, the functional implications are the same for both explanations; that is, motor learning results in an increased ability to reflexively orient attentional processes to novel stimuli.

Contrary to expectation, the amplitude of the LPP component was variable across the blocks for the control group only. Specifically, a reduction in amplitude was observed when participants were first introduced to the incongruent trials (block 7) as compared to blocks 2, 4 and 6. Although the control group received veridical feedback, they experienced the novelty of using their non-dominant hand and the removal of the effects of gravity. Thus, a modest degree of motor learning was required, albeit on a much simpler scale as compared to the learning group. In this regard, the control group may have progressed to the stage of automaticity as described by Fitts and Posner (1967) and, as such, allocated little to no cognitive resources to execute the task. As the LPP reflects higher-order non-obligatory cognitive evaluation of the stimuli, the development of such an advanced stage of motor learning likely allowed for the observed statistical difference of the LPP when the control group was finally exposed to the novel challenge (i.e., rotation). As such, there was a relative reduction in their ability to

dedicate cognitive resources to processing the sounds during their only exposure to the distortion (block 7 for control group) as compared to the apparent (i.e., nonsignificant) reduction observed in the learning group (between both blocks 1 to 2 and blocks 6 to 7). Longer exposure to the rotation would likely facilitate automaticity in the learning group, which would then have been disrupted to a greater degree when the distortion was finally removed. In summary, the LPP results suggest that changes in non-obligatory cognitive processes reflect alterations in task demand during the advanced stages of motor learning.

The present study emphasizes the need to consider the stage of learning in order to predict efficacy of decision-making and the quality of response when challenged with ‘surprise’ (i.e. unexpected) events. Specifically, expertise facilitates the ability to respond to unexpected events because of the enhanced availability of attentional resources. Accordingly, the present study provides objective, neurobiological evidence of the evolution of attentional reserve (i.e., increase) as cognitive-motor learning progresses. Such evidence can provide confidence in the trust placed in experts to perform under pressure. That is, they have the requisite resources with which to respond adaptively to ‘surprise’ when faced with sudden perturbations in the task environment. This ability to successfully respond, or conversely fail, to cognitive-motor challenge has significant and potentially “life or death” consequences. For example, in the realm of superior performance, an expert pilot would be more likely to respond effectively to unexpected engine failure, whereas one with less skill may not have the necessary resources available to attend to the crisis. Of course, the availability

of attentional reserve is necessary but not sufficient to predict behavioral success in response to heightened demand, as a repertoire of skill elements would also be needed. Finally, the relevance of the metric developed in the current study could be extended into clinical domains and employed to assess changes in the “mental effort” associated with performance throughout the course of rehabilitation. This assessment would provide objective evidence of the magnitude of recovery which serves to inform the capabilities of the patient, the effectiveness of the treatment, and thus aid the development of more successful rehabilitation strategies.

Appendix 1

Subject ID: _____ Date _____

Health Status Questionnaire

Date of birth _____ Age _____ Gender M _____ F _____

Hearing impairment Yes _____ No _____ If yes, describe

Are you presently wearing and or using, or have you ever worn or used either a pacemaker or a defibrillator _____

Do you currently or have you ever had any of the following medical disorders?

Heart attack Yes _____ No _____

Asthma Yes _____ No _____

Epilepsy or seizure disorder Yes _____ No _____

Psychiatric disorder Yes _____ No _____ if yes, what diagnosis _____

Medications: Are you presently taking any medications? If so:

Name what for? Dose/frequency last dose

1

2

3

Time since last intake of:

Caffeine _____ Tobacco _____ Alcohol _____

Appendix 2

Subject ID _____ Date _____

EDINBURGH HANDEDNESS INVENTORY

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put ++*. If in any case you are really indifferent *put + in both columns*. Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all of the questions, and only leave a blank if you have no experience at all of the object or task.

		Left	Right
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking match (match)		
10	Opening box (lid)		
i.	Which foot do you prefer to kick with?		
ii.	Which eye do you use when using only one?		

Appendix 3

Informed Consent:

Protocol Title: Changes in attentional processes as a function of motor learning

Study No.: HP-00044883

Sponsor: Veterans Affairs Administration

You have been invited to participate in a research pilot study that uses EEG to learn specific brain wave patterns associated with changes in attention while learning a reaching task. The findings will be used to assess motor learning interventions in the future in order to assist those in rehabilitation. If you are eligible and choose to participate, please be aware that your participation is voluntary and that you may ask questions at any time. Please note that your employment or your academic standing will not be affected in any way by your participation in this study.

PURPOSE OF STUDY

- The purpose of this research project is to learn the EEG brain wave patterns that are associated with changes in attentional processes during the course of motor learning. Such that, an objective measure of cognitive workload during rehabilitation can be developed.
- You may qualify for this study if you are a healthy adult between the ages of 18-44 years of age, right-handed, free of neurocognitive impairment, and must not report being pregnant.
- We expect to enroll approximately 40 participants at the Baltimore VA Medical Center (VAMC), which is the primary location where this study is being conducted.

• **PROCEDURES**

This study involves 1 visit to the Baltimore VAMC. The visit is described below:

- For the one visit you will come to the 6B research wing of the VA, the Upper Extremity Robotics Laboratory. First you will be asked to read and sign the consent form giving permission to participate in the study, and you will be given a copy. To determine your eligibility for this study, this visit will include a Health Status Questionnaire (HSQ) and an inventory that assesses your handedness (Edinburgh Handedness Inventory). to determine eligibility for the study. If the HSQ reveals a health problem, you will be referred to an appropriate health professional for follow-up. If the study requirements cannot be met after the HSQ then you will not be able to participate in this study. If you are female of childbearing age and wish to participate, you will be asked if there is any chance that you are pregnant, if there is any self-reported chance that you are pregnant, you may not participate.
- You will be asked to refrain from consuming any alcoholic beverages for 24 hours prior to your visit. Additionally, you will be asked to refrain from eating or

drinking large amounts of food or water (> 1 qt. of water, or a large dinner size meal, snacking & sipping are acceptable and encouraged), consuming caffeinated beverages or smoking for at **least one hour** prior to the visit.

- Upon arrival you will be fitted for an EEG cap, similar to a swim cap that will be placed on your head. The purpose of the cap is to record brain electrical activity. Other sensors will be placed on the skin above and below your left eye to record eye blinks and on your ear lobes or on the back of your neck to serve as a reference. These sensor sites will be lightly rubbed with alcohol and a special gel to improve the connection between the skin of the scalp and the sensors. Using a blunt applicator and syringe, the previously described conducting gel will be applied to each electrode site. You will feel a rubbing sensation but the skin will not be broken.
- Motor Learning (approximately 1 hour): During the visit, you will rest your left arm in a cradle on the air table and make movements to targets on the computer screen. It will be like playing a video game with your arm and you will get points for the movements you make. You will try to beat your own best score each game you play. At any point you can ask for a break, and breaks will be provided approximately every 8 minutes. You will also temporarily hear sounds at a comfortable loudness, but do not need to respond to these. Finally, you will respond with your other hand on a response pad to a secondary video game.
- Once the study is completed, the research results of this experiment will not be reported to your health care provider(s), however you can request to be notified about the final results once the study is completed.
- You will not be contacted after completion of the original research unless you have requested to learn about final results.

POTENTIAL RISKS/DISCOMFORTS:

- There are no major foreseeable risks or discomforts that you are likely to experience due to participation in this research. There are some potential minor risks or discomforts that may be experienced, and these are described below:
 - There is a minimal risk of temporarily localized muscle fatigue while performing the motor task. However, this fatigue usually subsides within 10 minutes after cessation.
 - From wearing the EEG cap you may experience slight sensations and irritation as the scalp is lightly rubbed at the electrode sites. There is some risk that your skin may be broken during the EEG cap preparation, however this is rare in our lab. Also, a small number of people may be allergic to the conducting gel and/or adhesive used to attach the other sensors on the skin, but this is rare. Please let us know if you are experiencing irritation around electrode placement areas. Lastly, if you experience a temporary reddening of the skin around any of the sensor sites, this goes away within an hour or so.
 - There is a small risk that there will be a loss or breach of confidentiality. Loss of confidentiality will be minimized by storing personal data in a locked office and locked cabinet. Also, all electronic data will be coded and stored on password-protected computers.
 - There may be risks in this study which are not yet known.

POTENTIAL BENEFITS

- There are no direct benefits to you for participating in this study. However, your participation may help investigators better assess the effectiveness of rehabilitation programs. .

ALTERNATIVES TO PARTICIPATION

- This is not a treatment study. Your alternative is to not take part. If you choose not to take part, your healthcare, employment, or student status at University of Maryland, Baltimore or the Veterans Affairs Maryland Healthcare System will not be affected.

COSTS TO PARTICIPANTS

- It will not cost you anything to take part in this study.

PAYMENT TO PARTICIPANTS

- Participants will be paid \$60 for taking part in this study.

CONFIDENTIALITY

- The study will involve use of confidential information. Study personnel will have access to the information, and it will be coded to protect your identity. The investigators will use the codes with all research data in electronic format, and all other files with confidential information will be stored in locked file cabinets within locked office or lab space. All study data will be securely stored as indicated above. Your research records and/or identifiers will be retained in accordance with the VA records control schedule. The “records control schedule” is a set of rules set by the federal government that states when federal agencies are allowed to dispose of records. The VA and VHA must follow these rules.
- The data from the study may be published. However, you will not be identified by name. People designated from the institutions where the study is being conducted and people from the sponsor will be allowed to inspect sections of your medical and research records related to the study. Everyone using study information will work to keep your personal information confidential. Your personal information will not be given out unless required by law. Study records can be reviewed by federal agencies, private sponsor, and the IRB.
- If you are a patient in the VAMHCS, the results of your medical tests for this study will be included in your medical record. Your medical and research records will be kept strictly confidential to the fullest extent permitted by law.
- The Veterans Health Administration (VHA) and its Offices may inspect your research records. Your research records will be stored at the VA Maryland Health Care System (VAMHCS).

RIGHT TO WITHDRAW

- Your participation in this study is voluntary. You do not have to take part in this research. You are free to withdraw your consent at anytime. Refusal to take part or to stop taking part in the study will involve no penalty or loss of benefits to which you are otherwise entitled. If you decide to stop taking part, if you have questions, concerns, or complaints, or if you need to report a medical injury

related to the research, please contact the investigator Larry Forrester, PhD at 410-605-7000 ext. 4321. There are no adverse consequences (physical, social, economic, legal, or psychological) if you decide to withdraw from this research study.

- There are no adverse consequences (physical, social, economic, legal, or psychological) of a decision to withdraw from the research.
- If you are an employee or student, your employment status or academic standing at UMB will not be affected by your participation or non-participation in this study.
- If you are a veteran wanting to confirm that this study is in fact IRB approved and is being conducted at the VAMHCS, you may contact Dr. Lauren Jones-Lush at 410-605-7000 ext. 4862.
- You may withdraw from this study at any time without penalty or loss of VA or other benefits to which you are entitled. Your participation will not affect the way you now pay for medical care at the VAMHCS.
- If you have any questions about the study please call 410-605-7000 ext. 4862.
- You will be told of any significant new findings which develop during the study which may affect your willingness to participate in the study.

UNIVERSITY STATEMENT CONCERNING RESEARCH RISKS

The University is committed to providing participants in its research all rights due them under State and federal law. You give up none of your legal rights by signing this consent form or by participating in the research project. Please call the Institutional Review Board (IRB) if you have questions about your rights as a research participant.

The research described in this consent form has been classified as minimal risk by the IRB of the University of Maryland, Baltimore (UMB). The IRB is a group of scientists, physicians, experts, and other persons. The IRB's membership includes persons who are not affiliated with UMB and persons who do not conduct research projects. The IRB's decision that the research is minimal risk does not mean that the research is risk-free. You are assuming risks of injury as a result of research participation, as discussed in the consent form.

The VA Maryland Health Care System will provide necessary medical treatment (not just emergency care) to a research subject injured by participation in a research project. This requirement does not apply to treatment for injuries that result from non-compliance by a research subject with study procedures. This care may be limited by local or federal law.

If you are harmed as a result of the negligence of a researcher, you can make a claim for compensation. If you have questions, concerns, complaints, or believe you have been harmed through participation in this research study as a result of researcher negligence, you can contact members of the IRB or the staff of the Human Research Protections Office (HRPO) to ask questions, discuss problems or concerns, obtain information, or offer input about your rights as a research participant. The contact information for the IRB and the HRPO is:

University of Maryland School of Medicine
Human Research Protections Office
BioPark I

800 W. Baltimore Street, Suite 100
Baltimore, MD 21201
410-706-5037

You may also contact the VAMHCS Office of Research Compliance (ORC). The contact information for the ORC is:

VAMHCS Office of Research Compliance
Baltimore VA Medical Center
10 North Greene Street, Mail Stop 151
Baltimore, MD 21201
410-605-7000, extension 6512
Room 3A-125

The VAMHCS ORC may contact you in the future to ask you about your experiences with this research study.

Signing this consent form indicates that you have read this consent form (or have had it read to you), that your questions have been answered to your satisfaction, and that you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form.

If you agree to participate in this study, please sign your name below.

Participant's Signature

Date: _____

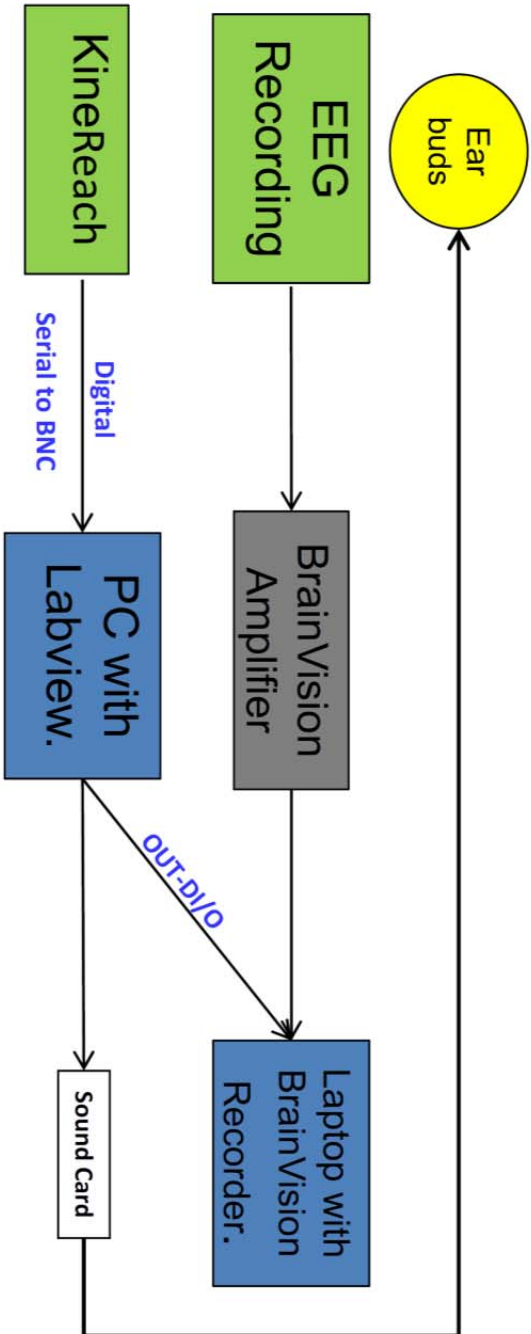
Investigator or Designee Obtaining Consent Signature

Date: _____

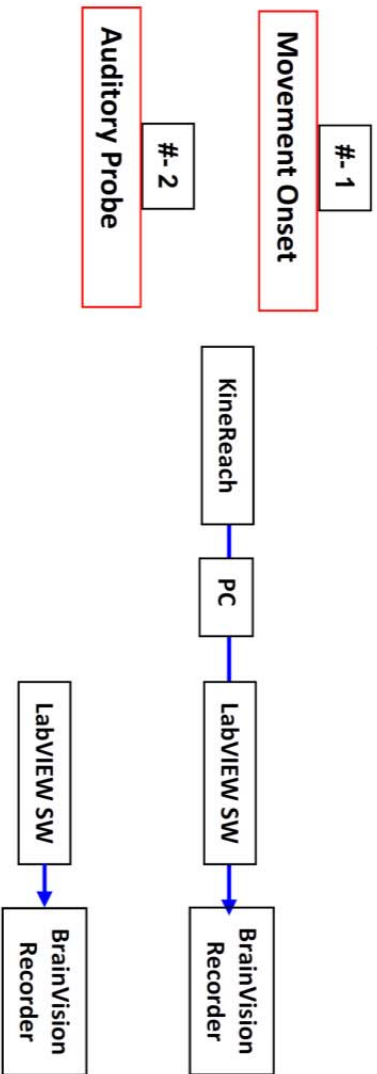
Witness

Date: _____

Equipment Interface:



Propagation of Triggering Information:



Appendix 5

Program that Calculates IDE from the Kinematic Data

```
%Code that processes the kinematic data from the Kinereach system
and
%outputs the variable IDE.
```

```
%Parameters are set up for Jeremy's Dissertation
```

```
%Written by Jeremy Rietschel, March 2011
```

```
%Basic Information
```

```
Fs = 130; %Sampling Freq
delta_t = 1/Fs; %sampling period
scrsz = get(0,'ScreenSize'); %gets screen size
Rot = 2; %Put 1 for congruent and 2 for rotated depending on
which
    %condition you are processing
```

```
%Vector of target sequence
```

```
Tar_seq = [1 6 3 2 4 5 3 7 8 2 1 1 6 7 3 6 4 4 5 7 8 7 3 2 4 1 5
2 6 5...
8 6 8 5 8 1 4 7 2 3 8 1 7 5 4 6 2 3 2 4 1 8 6 7 5 3];
```

```
%Matrix of degrees that correspond to the optimal trajectory for
the target
%sequence. 1--unrotated, 2--rotated.
```

```
Vec_tar =
[0,225,90,45,135,180,90,270,315,45,0,0,225,270,90,225,135,...
135,180,270,315,270,90,45,135,0,180,45,225,180,315,225,315,180,...
.
315,0,135,270,45,90,315,0,270,180,135,225,45,90,45,135,0,315,225,
...
270,180,90;60,285,150,105,195,240,150,330,15,105,60,60,285,330,..
.
150,285,195,195,240,330,15,330,150,105,195,60,240,105,285,240,15,
...
285,15,240,15,60,195,330,105,150,15,60,330,240,195,285,105,150,10
5,...
195,60,15,285,330,240,150];
```

```
%Plots the home and targets in space consistent with the
Kinereach space
```

```
figure;
%Circle locations
homecircle_loc = [.855;1.16];
```

```

targetcircle_loc =
[1.035,.982279,.855,.727721,.675,.727721,.855,.982279...
;1.16,1.287279,1.34,1.287279,1.16,1.032721,.98,1.032721];

%Plot the home circle
circle_r = .0125;
[x,y,z] = cylinder(circle_r,200);
plot(x(1,:)+homecircle_loc(1,1),y(1,:)+homecircle_loc(2,1));hold
on
axis equal
fill(x(1,:)+homecircle_loc(1,1),y(1,:)+homecircle_loc(2,1),'g');

%Plots the targets
for i = 1:8
[x,y,z] = cylinder(circle_r,200);hold on

plot(x(1,:)+targetcircle_loc(1,i),y(1,:)+targetcircle_loc(2,i));h
old on
axis equal

fill(x(1,:)+targetcircle_loc(1,i),y(1,:)+targetcircle_loc(2,i),...
.
[.5 .5 .5]);
end

axis([0.4609,1.2391,0.8275,1.4925]);

%Loads in files with the trajectories

%Select folder
pth = uigetdir('F:\_Kinerp\Behav_Data','Select location of the
files');
eval(['cd ',pth]);
d = dir;
str = {d.name};
[s] = listdlg('Name','Choose your files...',...
'OKString','Run it','CancelString','I Screwed
Up','ListSize',...
[300,400],'PromptString','Select a file:','SelectionMode',...
'multiple','ListString',str);

%In case someone hits 'select all' or chooses the index files (.
..)
%This loop will get rid of those files to avoid future errors
if s(1) == 1 || s(1) == 2;
s = s(2:length(s));
if s(1) == 2;
s = s(2:length(s));
end;
end;

%files are loaded in here
files = str(s);
for i = 1:length(files)

```



```

end

IDE(j) = t_D(j) - Vec_tar(Rot,j);

%If in wrong side of 0 degree this will correct for the
%error

if Vec_tar(Rot,j) >= 0 & Vec_tar(Rot,j) <= 90
    if t_D(j) >= 270;
        IDE(j) = t_D(j) - Vec_tar(Rot,j) - 360;
    end
elseif Vec_tar(Rot,j) >= 270 & Vec_tar(Rot,j) <= 360
    if t_D(j) <= 90;
        IDE(j) = t_D(j) - Vec_tar(Rot,j) - 360;
    end
end

end

%Plots inforation for visual inspection
figure;
figure('Position',[25,25,scrsz(3)-50,scrsz(4)-50]);
subplot(1,5,1:4);
%plots the targets
circle_r = .0125;
[x,y,z] = cylinder(circle_r,200);
plot(x(1,:)+homecircle_loc(1,1),y(1,:)+...
    homecircle_loc(2,1));hold on
axis equal
fill(x(1,:)+homecircle_loc(1,1),y(1,:)+...
    homecircle_loc(2,1),'r');

%Plots the targets
for i = 1:8
    [x,y,z] = cylinder(circle_r,200);hold on
    plot(x(1,:)+targetcircle_loc(1,i),y(1,:)+...
        targetcircle_loc(2,i));hold on
    axis equal
    fill(x(1,:)+targetcircle_loc(1,i),y(1,:)+...
        targetcircle_loc(2,i),'b');
end

axis([0.4609,1.2391,0.8275,1.4925]);

%plots ideal trajectory
plot([homecircle_loc(1),targetcircle_loc(1,Tar_seq(j))],...
    [homecircle_loc(2),targetcircle_loc(2,Tar_seq(j))],'k');
%axis([0.4609,1.2391,0.8275,1.4925]); hold on;
axis equal; hold on;

%plots actual trajectory
plot(datafilt{1,j}(:),datafilt{2,j}(:),'b');
plot(datafilt{1,j}(1:100),datafilt{2,j}(1:100),'r');

%plots where IDE was calculated from
plot(datafilt{1,j}(pvi(j)),datafilt{2,j}(pvi(j)),'rx');

```

```

%plots IDE on the graph
text(.6,.9,['IDE =',num2str(IDE(j))]);

%plots velocity and where IDE was calculated from
subplot(1,5,5);
plot(vel); hold on; plot(pvi(j),pv(j),'rx')

%Approve or Reject the IDE
button = questdlg2('Please Confirm','Confirm Markers?'...
, 'Yes','Reject','Yes');
if strcmp(button,'Reject')
    IDE(j) = nan;
end

close all
end

%Grabs first two trials to each target
IDE2 = IDE([1 11 4 10 3 7 5 17 6 19 2 13 8 14 9 21]);

%Displays the IDE that will go into the average
IDE2'

%Calculates the mean for inferential statistics
mIDE = nanmean(IDE2,2)

```

Appendix 6
All Post Hoc Comparisons and Effect Sizes for IDE

Tukey HSD for each Group: **IDE**

Control
:

Mean Square Error	12.229		<u>Mean</u>	<u>Std.Dev.</u>
df Error	36	Block 1	0.641	1.6
n	10	Block 2	1.665	1.216
k	5	Block 4	1.559	1.501
		Block 6	1.413	1.769
q stat .05	4.1	Block 7	-37.422	4.611
q stat .01	5.05			
	4.53397			
q-criterion at p = .05	7			
q-criterion at p = .01	5.58453			
	3			

Mean Differences	Block 1	Block 2	Block 4	Block 6	Block 7
Block 1		-1.024	-0.918	-0.772	38.063
Block 2			0.106	0.252	39.087
Block 4				0.146	38.981
Block 6					38.835
Block 7					

Effect Sizes	Block 1	Block 2	Block 4	Block 6	Block 7
Block 1		0.72727 3	0.59206 7	0.45829 6	12.2566 4
Block 2			0.07802 7	0.16884 4	13.4158 2
Block 4				0.08929 7	12.7555 6
Block 6					12.1739 8
Block 7					

Tukey HSD for each Group: **IDE**

Learning
:

Mean Square Error	52.23		<u>Mean</u>	<u>Std.Dev.</u>
df Error	40	Block 1	0.396	1.823
n	11	Block 2	-35.811	5
k	5	Block 4	-12.034	6.81
		Block 6	-9.219	5.393
q stat .05	4.04	Block 7	25.08	7.254
q stat .01	4.93			
q-criterion at p = .05	8.80329			
q-criterion at p = .01	10.7426			

Mean Differences	Block 1	Block 2	Block 4	Block 6	Block 7
Block 1		36.207	12.43	9.615	-24.684
Block 2			-23.777	-26.592	-60.891
Block 4				-2.815	-37.114
Block 6					-34.299
Block 7					

Effect Sizes	Block 1	Block 2	Block 4	Block 6	Block 7
Block 1		10.6132 2	2.87964 8	2.66491 1	5.43880 1
Block 2			4.02658 8	5.11729	9.93814 3
Block 4				0.46136 2	5.27787 3
Block 6					5.42405 3
Block 7					

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