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Psychophysiological support of increasing attentional reserve during the development of a motor skill*

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Abstract

The aim of this study was to determine the relationship between motor skill and attentional reserve. Participants practiced a reaching task with the dominant upper extremity, to which a distortion of the visual feedback was applied, while a control group performed the same task without distortion. Event-related brain potentials (ERPs), elicited by auditory stimuli were recorded throughout practice. Performance, as measured by initial directional error, was initially worse relative to controls and improved over trials. Analyses of the ERPs revealed that exogenous components, N1 and P2, were undifferentiated between the groups and did not change with practice. Notably, amplitude of the novelty P3 component, an index of the involuntary orienting of attention, was initially attenuated relative to controls, but progressively increased in amplitude over trials in the learning group only. The results provide psychophysiological evidence that attentional reserve increases as a function of motor skill acquisition.

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Keywords

Motor learning; Attention; Novelty-P3; EEG; Event-related potential

1. 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 physiological resources as one becomes proficient. Efficiency is traditionally characterized by the effort required for work output and can be quantified by increased force per motor unit (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002), enhanced inter-limb coordination (Lay, Sparrow, Hughes, & O'Dwyer, 2002), streamlined neural resource allocation (Hatfield, Haufler, Hung, & Spalding, 2004; Hatfield & Hillman, 2001), and greater focus on task-relevant cues (Williams, 2002), etc. In tandem with changes in efficiency are modifications in attentional processes. Phenomenological reports and behavioral studies suggest a positive relationship between increasing proficiency and attentional reserve (Magill, 2007). Specifically, Magill suggests that attentional demands are high during the early stage of motor learning, but then decrease as skill is acquired. Although some have investigated the neural underpinnings of this relationship (Maclin et al., 2011), psychophysiological evidence of the dynamic relationship between attention and motor learning is limited.

Attention refers to the directed allocation of cognitive resources. Attention is quantitatively limited, and the total quantity available is referred to as attentional capacity (Schmidt & Wrisberg, 2008). As one engages in a task, attentional resources are drawn from this capacity, thus reducing attentional reserve. Reserve is further consumed when 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 resources compared to simple tasks. If attentional resources are low, one's performance on a single, or on multiple tasks may diminish (Magill, 2007; Strayer, Drews, & Johnston, 2003). 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 wherein motor sequences become routine, thus decreasing the attentional resources associated with the execution of a given task.

Supporting this notion, 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). Employing a golf putting task, Beilock, Wierenga, and Carr (2002) observed that experience enabled performers to spare attentional processes associated with primary 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, MacMahon, & Starkes, 2002; Grey, 2004). The effect of expertise is evident even in tasks that require minimal attention such as postural control, e.g., expert gymnasts relied less on attentional processes during a unipedal balance task (Vuillerme & Nougier, 2004). Reductions in required attentional

resources as motor learning progresses are hypothesized to result from changes in the neural networks that underlie these behaviors.

Neurobiological investigations of motor learning suggest that skill acquisition is marked by refinements in cortical dynamics (Bell & Fox, 1996; Busk & Galbraith, 1975; Gentili, Bradberry, Hatfield, & Contreras-Vidal, 2009; Haier et al., 1992; Hatfield et al, 2004; Kerick, Douglass, & Hatfield, 2004). A likely outcome of this “streamlining” is an increase in the neural resources available for attentional demands beyond those associated with the primary motor task, i.e., an increase in attentional reserve (Weissman, Roberts, Visscher, & Woldorff, 2006). However, the physiological processes associated with this shift have not been unambiguously investigated during the execution of a single task. Dual-task studies have revealed behavioral and psychophysiological changes in attention with learning (Maclin et al, 2011). However, Kramer, Wickens, & Donchin, 1985, advanced the notion that dual-task investigations characteristically confound measurement of primary task (i.e., the task of interest) outcomes as the two tasks compete for neural resources.¹

The probing of attention across the process of motor learning has not been investigated using psychophysiological measures of attentional dynamics during a single-task paradigm. This approach would provide a means to confirm the assumption that the demand on attentional resources reduces as one becomes proficient at a given task. In this regard, psychophysiological methods have been employed successfully to assess other cognitive processes (Humphrey & Kramer, 1994; Kerick, Hatfield, & Allender, 2007; Parasuraman, 1980; Senkowski & Herrmann, 2002). Specifically, components of the event related potential (ERP), derived from electroencephalography (EEG), have been used to infer the amount of cognitive resources consumed by a given task (Miller, Rietschel, McDonald, & Hatfield, 2011).

For example, to investigate cognitive workload as a function of task 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. Notably, they employed a modified oddball, which relative to the standard oddball, replaces common tones with silence eliminating the need for the participant to engage in tone discrimination or any need to respond. Most importantly, this modified oddball provided a means to assess cognitive processes during single-task execution (i.e., without confounds associated with dual tasks). Allison and Polich observed a reduction in both exogenous and endogenous ERP components elicited by the tone as workload (game difficulty) increased, suggesting that task difficulty was positively related to cognitive workload. Similarly, Miller et al. (2011) incrementally varied the difficulty of a visuomotor task (Tetris®) by manipulating game speed, while employing the modified oddball task. However, they presented novel sounds (e.g., dog bark) instead of pure tones. This approach was advantageous as such sounds have been shown to be more specific to attentional reserve. Such sounds elicit many of the same ERP components as the traditional

¹However, there are scenarios in which dual task approaches are desirable. For example, such an approach would be useful if one were specifically interested in evaluating how neurocognitive resources are distributed between tasks when multitasking (see Maclin et al., 2011).

oddball (Polich & Margala, 1997) even when ignored (Mertens & Polich, 1997), while being more robust to any habituation effects associated with repetitious stimuli (Wetter, Polich, & Murphy, 2004). Moreover, novel sounds elicit the novelty P3 component; its amplitude reflects the magnitude of attentional resources available for the compulsory orienting response (Friedman, Cycowicz, & Gatea, 2001; McDonald, Gabbay, Rietschel, & Duncan, 2010; SanMiguel, Morgan, Kiein, Linden, & Escera, 2010). Miller et al. observed an inverse relationship between amplitude of the novelty P3 and task difficulty positing this as a viable method to assess attention reserve during single-task execution. However, both of these studies examined the role of task difficulty, rather than investigating the impact of skill acquisition (i.e., motor learning), on attentional processes.

Thus, the purpose of this study was to provide confirmatory psychophysiological evidence of the positive relationship between motor skill acquisition and attentional reserve, as noted above, using the modified oddball task while employing novel sounds. In the present study, participants were challenged to become proficient on a novel visuomotor task through the employment of many trials. The visuomotor task involved center-out reaching movements that required resolution of a distortion between visual and proprioceptive feedback, a method commonly employed to study motor skill acquisition (see Krakauer, 2009 for review). We predicted that the novelty P3 amplitude would initially be attenuated (suggesting reduced attentional reserve), but would progressively increase in amplitude throughout the task (suggesting increases in attentional reserve).

2. Methods

2.1. 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 25.00 (2.70), ranged 21–30). All participants reported being free of neurological disorders and hearing impairment as determined by a health status questionnaire (HSQ). Additionally, all participants were right-handed as determined by the Edinburgh handedness inventory (EHI). Finally, all participants provided informed consent on a form approved by an 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, $t(19) = .240$, $p > .05$, Control Group, $M = 24.80$ (2.66), Learning Group, $M = 25.18$ (2.86).

2.2. Instrumentation

2.2.1. Experimental setup—Participants were seated directly in front of a visuomotor research apparatus (Wang & Sainburg, 2005) with both their hands resting on a flat horizontal surface. Approximately 13" above the surface upon which their hands' rested was a horizontal mirror that occluded the participants' view of their hands. Additionally, the mirror displayed the visual stimuli associated with the visuomotor task (i.e., start circle, target, and 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. Data were collected with a sampling rate of 130 Hz. 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 (60 Hz) to maintain perception of the cursor and hand location as consistent with 'real time'. 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).

2.2.2. 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 increase both: (1) the time needed to become competent at this relatively simple task and (2) the consumption of attentional resources, thus 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 gray with a 2.5 cm diameter. Targets were located 18 cm from the home circle radially and equally spaced apart, see Fig. 1. The participant was instructed to wait in the home circle for at least 2s and then to move as quickly and accurately (straight line) to the target that is currently displayed. Each trial lasted a total of 6s (2s prior to movement onset and an additional 4s after movement onset). If the target was reached before 4s had elapsed the participant remained inside the target circle for the remaining duration of the trial. At the end of the 6s, the movement path was displayed for 2s 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° counterclockwise rotation, such that for a given trajectory, participants observed their cursor moving 60° distorted from their actual movement (Fig. 1). 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 required participants to compensate for the visual distortion in order to successfully perform the motor task.

2.3. Auditory probe, modified-oddball task

Thirty stimuli were randomly selected from a larger set of 96 sounds obtained from the New York State Psychiatric Institute (Fabiani, Kazmerski, Cycowicz, & Friedman, 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.

2.3.1. Psychophysiological recordings—Electroencephalographic data were collected using an actiCAP EEG system (Brain Products GmbH, Munich, Germany) and were acquired from 64-sites, 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 kΩ 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)

2.4. 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 kΩ) 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. Participants heard the same set of sounds during each of the seven blocks. However the order of the presentation was randomized within each block. 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 move as quickly and accurately to the target circles after waiting in the home circle for at least 2s. 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 2s. Participants were told that the sounds were irrelevant to the task and there was no objective with regard to the sounds.

2.5. Data processing

Kinematic data from the visuomotor task were processed using in-house software 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 as described in King, Kagerer, Contreras-Vidal, and Clark (2009). As few as six trials are needed to obtain a stable estimate of learning, two trials for each target. 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, Pine, Ghilardi, & Ghez, 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-s sweeps (± 2 s 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, Westerfield, Townsend, & Makeig, 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 1s 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). In contrast to the desired number of trials used for the IDE analysis as described above, at least 20 trials were required for the generation of the ERP to obtain an adequate signal to noise ratio (Cohen & Polich, 1997).

The windows corresponding to each of the component average amplitudes were initially determined by averaging across all subjects and blocks. Next, the latency for each component was identified by the peak amplitude and then a window around this peak was chosen, an approach advocated by Handy (2005) and Luck (2005). Average amplitude was calculated for each component and current source densities were computed. These were projected on the scalp to establish that the observed topographic distribution for each window was consistent with those described in the literature, see right side of Fig. 2. The resultant windows were: N1 = 100–120 ms, P2 = 170–210, and novelty P3 = 250–290 ms. Finally, average amplitudes were computed for each subject and block using these windows at the midlines electrode sites, Fz, Cz, and Pz.

2.6. Statistical analysis

The kinematic variable IDE was subjected to a 2 (Group) $\times$ 5 (Block) ANOVA. 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 three ERP component average amplitudes was subjected to separate 2 (Group) $\times$ 5 (Block) ANOVAs with the addition of the factor Region (Fz, Cz, and Pz). Thus, three 3-factor ANOVAs were computed for the ERP components. The decision to remove adjacent blocks (3 and 5) from the statistical analysis was made in order to contrast processes associated with distinct phases of motor learning. Given that motor learning occurs in a continuous manner, adjacent blocks are unlikely to reflect distinct phases. Nonetheless, a blocked design was necessary given that many trials need to be averaged to obtain a single quality measurement, particularly with regard to the ERP.

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 Section 3.

3. Results

3.1. Kinematic analysis

The statistical analysis examining IDE revealed a significant Group $\times$ 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 ($t(19) = .326, p = .748, d = 0.14$). The learning group was significantly greater (in the negative direction) for

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. These Group comparisons by Block are conveyed on the left side of Fig. 3.

Separate one-way ANOVAs were conducted to determine the dynamics of IDE across the blocks for each group. The ANOVA applied to the control group was significant ($F(4,36) = 663.81, p < .001, \varepsilon = .43$). Post hoc analyses were performed using Tukey's HSD and revealed that IDE was significantly greater (in the negative direction) during block 7 only 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. As expected, blocks for which there was no distortion (i.e., 1, 2, 4, and 6) were undifferentiated. See right side of Fig. 3. In addition, the ANOVA applied to the learning group revealed a significant for block ($F(4,40) = 200.22, p < .001, \varepsilon = .64$). Tukey's HSD post hoc analysis revealed multiple significant findings for IDE in the learning group, thus for clarity, only comparison of adjacent blocks are reported. IDE was higher during the initial distortion compared to baseline and was progressively attenuated across blocks involving the distortion. Specifically, that IDE was greater (in the negative direction) during block 2 as compared to block 1 ($p < .01, d = 10.61$). IDE became 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 greater (in the positive direction) during block 7 relative to block 6 ($p < .01, d = 5.42$) suggestive of after-effects, see right side of Fig. 3.

3.2. ERP analyses

The left side of Fig. 2 contains the ERPs of each group from which the following components were derived for the learning blocks only.

3.2.1. N1 component—No significance was observed with regard to Block and Group for the N1 component, $F(8,12) = 1.15, p = .40$.

3.2.2. P2 component—No significance was observed with regard to Block and Group for the P2 component, $F(8,12) = 1.23, p = .66$.

3.2.3. Novelty P3 component—The Group $\times$ Block $\times$ Region ANOVA revealed a significant 3-way interaction ($F(8,152) = 2.29, p = .05, \varepsilon = .59$). To determine the nature of this interaction, 3-separate Group $\times$ Block ANOVAs were conducted for each region.

For the Fz region, there was a significant Block $\times$ Group interaction ($F(4,76) = 6.47, p < .001, \varepsilon = .92$). To determine the effect of Group for each block a series of five independent t-tests was employed. These analyses revealed that the groups were undifferentiated during block 1 ($t(19) = 0.21, p = .839, d = 0.09$). 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. These Group comparisons by Block are conveyed on the left side of Fig. 4.

To determine the dynamics of novelty P3 (at the Fz electrode) across the blocks for each Group, separate one-way ANOVAs were computed for each group for the factor Block. The ANOVA applied to 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. As expected all block comparisons in which there was no distortion were undifferentiated. See right side of Fig. 4. In addition, the ANOVA applied to the learning group also revealed a significant effect of block ($F(4,40) = 6.82, p < .001, \varepsilon = .89$). Tukey's HSD post hoc analysis revealed that the novelty P3 was reduced during block 2 as compared to block 1 ($p < .01, d = 0.71$). The novelty P3 was greater in block 6 as compared to block 2 ($p < .01, d = 0.97$). Finally, the novelty P3 was reduced during block 7 as compared to block 6 ($p < .05, d = 0.54$), see right side of Fig. 3.

For the Cz electrode, there was a significant Block $\times$ Group interaction ($F(4,76) = 3.63, p < .01, \varepsilon = .92, \varepsilon = .59$). 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, $p > .05$.

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 applied to the control group was significant ($F(4,36) = 5.92, p < .001$). Similar to Fz, post hoc analyses were performed using Tukey's HSD and revealed that novelty P3 was 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 ($p < .01, d = 1.43$). In addition, the ANOVA applied to 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 reduced during block 2 as compared to block 1 ($p < .01, d = 0.90$). The novelty P3 during block 4 was not greater as compared to block 2 ($p > .05$), but was also reduced as compared to block 1 ($p < .05, d = 0.56$). In addition, the novelty P3 was greater in block 6 as compared to block 2 ($p < .05, d = 0.82$). Finally, the novelty P3 during block 7 was reduced as compared to block 1 ($p < .05, d = 0.65$).

As expected, the Group $\times$ Block ANOVA for the Pz electrode yielded no significance.

4. Discussion

The aim of this study was to examine the relationship between motor skill acquisition and attentional reserve using a neurobiological approach. 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. 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 provide

objective psychophysiological support for the construct that attentional reserve increases as a function of skill level across the course of motor learning while avoiding the limitations associated with a dual-task approach.

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 performance of the control group in block 2. This initial reduction in performance (as a consequence of the rotation) allowed for observation of the participants' adaptation to the distortion and thus allowed for the study of motor learning. The learning group reduced their IDE between blocks 2 and 4 and then 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) the control group performed similarly as when the learning group was exposed to the distortion in block 2. The pattern of adaptation exhibited by the learning group during the visuomotor distortion and relative to the control group provided a platform upon which to study the dynamics of attentional processes as a function of motor learning.

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). In this study, the novelty P3 derived from the signal at the Fz electrode: (1) was undifferentiated between the two groups prior to the distortion, and (2) was reduced in the learning group during block 2 relative to both the control group during block 2 and the learning group prior to the demands elicited by the distortion. This suggests that more cognitive neural 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 corresponding increase in the amplitude of the novelty P3.² This predicted increase suggests a progressive reduction in the attentional demand imposed by the primary task across the course of learning, thus making more attentional resources available for processing the sounds. Interestingly, no significant differences were observed with regard to group or block for either the N1 or P2 components, suggesting comparable stimulus detection across all conditions. Thus, motor learning appears to have selectively affected the reflexive orienting of attention to the probes.

Importantly, during late learning (block 6), the novelty P3 amplitude was undifferentiated from that observed prior to the distortion. Moreover, when the visuomotor distortion was

²Of note, the vast majority of ERP studies demonstrate a reduction (or sustained) in component amplitude over time for a fixed stimulus/experimental condition, whereas the present study revealed an increase.

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 unchanged until the introduction of the distortion (block 7), during which there was a significant reduction in 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.

The pattern of novelty P3 amplitude across the blocks for both groups, in conjunction with consideration of the functional neuroanatomy of the sources of the novelty P3, suggests that novel tasks impose a physiologically verifiable burden on attentional processes. Importantly, the increased burden becomes reduced across the course of cognitive-motor learning, thus ‘freeing up’ attentional resources. 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 their ability to shift visual attention between 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.

The current study was necessary, but not sufficient, in establishing the role of learning-dependent changes in attention in responding to ‘surprise’ or unexpected events. In this regard, future work should consider the response to imperative stimuli presented periodically throughout motor learning. Such evidence would 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 or elevations in task demand. The present finding only suggests that the “freeing-up” of attentional resources conferred to experts as a result of motor-learning would facilitate an enhanced ability to respond. However, the present study provides essential and objective, neurobiological evidence of the progressive increase of attentional reserve as a function of cognitive-motor learning.

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Fig. 1.

Task description. The left panel illustrates an optimal trajectory of a non-rotated (congruent) trial with veridical visual feedback, both represented by the solid line. On the right, a rotation trial (incongruent) is shown with the same motor behavior (solid line) along with the visual feedback a participant would observe for that behavior (dotted line). Note: for a given trial only one target was displayed at a time.

Fig. 2. ERP components. On the left are the averaged ERPs for both groups during the blocks included in the statistical analyses. On the right are the current source density plots for each of the three ERP components projected onto the scalp topography.

Fig. 3. 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, ** $p < .01$, *** $p < .001$.

Fig. 4. 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, * $p < .05$, ** $p < .01$.