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Draining your Brain: The Effects of Four Fatiguing Task Domains on Executive Function and Prefrontal Cortex

Salim A. Mouloua
University of Central Florida



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DRAINING YOUR BRAIN: THE EFFECTS OF FOUR FATIGUING TASK
DOMAINS ON EXECUTIVE FUNCTION AND PREFRONTAL CORTEX

by

SALIM ADAM MOULOUA

A thesis submitted in partial fulfillments of the requirements
for the Honors in the Major program in Psychology
in the College of Sciences
and in the Burnett Honors College
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Thesis Chairs: Dr. Daniel McConnell and Dr. Corey Bohil

Abstract

The present study empirically examined the effects of four fatiguing task domains on executive function through participants' reaction time, accuracy, and brain activity in prefrontal cortex (PFC). Forty college-age participants were collected (16 males and 24 females), of which eleven were examined using a functional near-infrared spectroscopy (fNIRS) imaging system. The present study used a 4×2 mixed factorial design consisting of fatiguing task (arm contractions task, vigilance task, distance-manipulated Fitts' task, size-manipulated Fitts' task) as a between-participant variable and *n*-back testing period (pre-test versus post-test 3-back task) as a within-participant variable. Results indicated significant increases in 3-back performance after the fatiguing tasks, and significant increases in 3-back compensatory brain activity in dorsomedial and dorsolateral prefrontal cortex (dmPFC and dlPFC) after the fatiguing tasks. Furthermore, results showed an interaction between 3-back target type and fatiguing task on standardized changes in reaction time, and an interaction between fatiguing task and testing period on brain activity in dmPFC. Theoretical and practical implications are discussed. Findings from this study may be used to help draw the boundaries on different domains of fatigue and their effects on the brain and body.

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CHAPTER 1: INTRODUCTION

Movement propels humans through innumerable daily tasks through controlled and autonomous processes. For any movement, it may be said that increasing levels of autonomy emerge with skill development, with learning progressing through multiple stages (Eversheim & Bock, 2001; Fitts, 1964; Fitts & Posner, 1967; Taylor & Ivry, 2012). In Fitts and Posner's model of skill acquisition, learning progresses through three stages, consisting of the cognitive stage, associative stage, and autonomous stage (Fitts & Posner, 1967; Taylor & Ivry, 2012; Wulf, 2007). Proficiency increases logarithmically as practice increases, indicating that the rate of skill acquisition decreases across the stages. Fundamentally, all behavior is movement guided by the elusive "black box" of the mind, and the study of behavior is the realm of psychology (Adolph & Berger, 2005). Thus, the empirical study of movement is penultimately important to psychology, as behaviors are measured in the physical world (Rosenbaum, 2005). Intriguingly, the study of movement has not heavily permeated psychology since the cognitive revolution in the 1950s (Rosenbaum, 2005), where Fitts' Law and similar advances in cybernetics were the driving forces in understanding human information-processing based on mathematical models such as Shannon's Information Theory (Fitts, 1954; Proctor & Vu, 2006; Shannon & Weaver, 1949).

The development of movement is inextricably entwined with cognitive and perceptual abilities, such that perception serves as a closed-loop mechanism to improve movements' effectiveness, efficiency, and safety (Adams, 1971; Adams, 1976; Elwell & Grindley, 1938). As such, afference provides perceptual information to guide efference, a cycle which developmentally begins early in humans. This developmental model for integrated movement and perception emerges in infancy – where infants use perceptual information to inform their

movements, and developments in movements lead to new perceptual experiences (Adolph & Franchak, 2016; Adolph & Joh, 2007; Thelen, 1995). Furthermore, early childhood development is marked with increases in general behavioral performance, such as decreases in motor performance (increased reaction time) and increases in processing speed, working memory (WM), and general intelligence (Leversen et al., 2012). Figurehead theorists in developmental psychology have also long touted the significance of gross and fine motor skill development for general psychological development, as motor behavior and other psychological behaviors are heavily entangled (Adolph & Franchak, 2016; Piaget, 1954; Gibson, 1988; Thelen & Smith, 1996). Late adolescent motor development, following late childhood development, is widely regarded as the peak developmental stage of motor performance (Malina, 2014; Zech et al., 2018) – the developmental locus of our proposed study.

CHAPTER 2: RELEVANT RESEARCH

Executive Function

A variety of tasks have been used to measure components of executive function, including simple (Case, Kurland, & Goldberg, 1982) and complex span tasks (Wilhelm, Hildebrandt, & Oberauer, 2013). Two facets of executive function, short-term memory (STM) and working memory (WM), are both concerned with short-term encoding and retention. However, the defining difference between STM and WM is the nature of usage – as WM is concerned with not only the retention of short-term information, but its manipulation in tasks that require cognitive-physical engagement (Baddeley & Hitch, 1974; Baddeley, 2000). Recent literature has indicated that STM and WM may have greater overlap than previously assumed (Aben, Stapert, & Blokland, 2012). The full realm of executive functions may not be fully dissociable, but WM is generally considered to address functions of higher cognitive load and complexity. One hallmark measure of working memory capacity (WMC), the individual differences construct of WM, is the *n*-back task. The *n*-back task has long been purported to measure different facets of cognition, such as executive control, attention, and verbal memory (Gajewski, Hanisch, Falkenstein, Thönes, & Wascher, 2018). However, in younger populations the *n*-back task has been largely associated with executive control – the locus of our present study. Studies using the *n*-back task have traditionally measured participants' reaction time and accuracy in response to targets and non-targets presented pictorially, textually, or auditorily. Here, we use one of the harder variations of the *n*-back task

Fitts' Law

Historically, Fitts' Law has been well established as the most robust tool for understanding movements in one-dimensional and two-dimensional response space in the three-dimensional world. Some studies have even confirmed the applicability of Fitts' Law to movements in three-dimensional response space (Campbell et al., 2008; Murata & Iwase, 2001; Zeng et al., 2012). The law has been used across various domains of psychology since its inception in Paul Morris Fitts' seminal paper (Fitts, 1954; MacKenzie, 1992). Hailing as one of the few scientific laws in psychology, Fitts' Law has been replicated across participants and conditions, serving as a predictor model for human movement. The origins of Fitts' Law stem from the speed-accuracy trade-off, where R. S. Woodworth first investigated the relationship between speed and accuracy in goal-directed aiming prior to the 19th century (Elliott et al., 2001; Hancock & Newell, 1985; Missenard et al., 2009; Woodworth, 1899). As Fitts' Law applies to all one-dimensional human movements, its applications range from performance in surgery, to driving, to reaching with a computer mouse (Mouloua et al., 2017, Mouloua et al., 2018). Fitts' equation is defined as $ID = \log_2(2D/W)$, where the index of difficulty (ID) indicates the task's difficulty in bits, where the distance between targets (D) is amplified and compared against the width of the individual targets (W), and the base 2 logarithm is taken against the ratio between distance and width for individual trials. The logarithmic function is inverse to an exponential function in an analogous manner that a square root is inverse to a squaring function – where we find the base to a squared number. The expansion into human performance can be determined by the equation $IP = ID/MT$, where the index of performance (IP) indicates a participant's slope of performance in a given task in bits per second, movement time (MT) reflects a participant's

initial movement time in seconds across N number of trials, and ID represents the difficulty in bits across N number of trials.

Movements occur in appendages such as the limbs, digits, heads, tongue, and lips of various organisms, though their usage in Fitts' Law has most prominently been recorded in humans (MacKenzie, 2018). Notably, movements of these appendages all form the basis of behavioral research, a strong testament to how combinations of peripheral movements guided by the central nervous system create most behaviors (Bootsma et al., 2004). A variety of Fitts' studies have also examined the role of manual asymmetries in the domains of attention, bimanual coordination, whole-body limb tapping, and imagined task performance (Amazeen & Ringenbach, 2005; Hoffmann, 1997; Maruff et al., 1999; Mouloua et al., 2017; Mouloua et al., 2018; Rohr, 2006). These studies shed light on the significant role of laterality in appendages' performance, where accrued experience and training between asymmetries explains individual differences in performance. The scope of the present study encompassed strongly right-handed participants alone, in order to reduce confounding variables of laterality and prioritize skill from experience alone (Mouloua et al., 2018).

Defining Fatigue

Broadly defined, fatigue is a psychophysiological state of exhaustion. Due to the multidimensional nature of fatigue, research has been pioneered in domains ranging from exercise physiology, cognitive psychology, human factors psychology, to medicine (Pattyn et al., 2018). In clinical research, chronic fatigue (persisting over six months) is generally the locus of longitudinal research into fatigue-symptomatic disorders (Fernandez et al., 2009). In non-

clinical research, fatigue is voluntarily induced in experiments through mental or physical exercise. The distinction between the two terms is the timescale (long-term or short-term) and nature (non-voluntary or voluntary) of the fatigue. Voluntary fatigue can be defined as a decrease in performance following psychophysiological exertion. The scope of the proposed study specifically encompasses voluntary fatigue, henceforth referred to as fatigue.

Fatigue has been studied across various task domains, usually falling under the umbrella of cognitively demanding or physically demanding tasks. Cognitively demanding tasks emphasize perceptual engagement, whilst physically demanding tasks emphasize physical engagement. However, in practice the two are difficult, if not impossible, to dissociate – as the foundation of all behavioral tasks involves stimulus perception and behavior. In physically demanding tasks, fatigue is elicited through physical workload and is denoted as physical fatigue or neuromuscular fatigue (Latash et al., 2003). In cognitively demanding tasks, fatigue is elicited through mental workload and is denoted as cognitive or mental fatigue (Helton et al., 2010). The distinction between cognitive and physical fatigue in the scientific literature often relies on central and peripheral factors, respectively (Mehta & Parasuraman, 2013). However, the interaction between cognitive and physical fatigue is scarcely observed, and thus poses a significant gap in the literature. The contributing central factors in both cognitive and physical fatigue are also unclear, with no studies directly comparing between the two. Previous studies have indicated that cognitive fatigue (Causse et al., 2017; Helton et al., 2010; Loris et al., 2005; Wang et al., 2016,) and physical fatigue (Dai et al., 2001; Liu et al., 2002; Liu et al., 2007; Thomas & Stephane, 2008) each are accompanied by compensatory neural mechanisms for maintaining task engagement. However, few studies have empirically examined the central and

peripheral factors of both cognitive and physical fatigue, which limits our understanding of where these relationships converge and diverge (Mehta & Parasuraman, 2013). Some experiments have investigated mental-physical workload interactions on fatigue (Bray et al., 2012; Granek & Sergio, 2015; Mehta & Agnew, 2012; Mehta & Parasuraman, 2013; Shortz et al., 2015), but few have examined central contributors to both types of workload (Mehta & Parasuraman, 2013). Understanding the neural generators of different types of workload is imperative to advancing our scientific knowledge of human exhaustion and will enable us to better categorize different types of fatigue. In the proposed study, we intended to induce physical fatigue through repeated isometric contractions with a resistance band (light load) and a distance constrained Fitts' task. Furthermore, we intended to induce cognitive fatigue through a vigilance task consisting of correctly identifying targets versus non-targets and a size constrained Fitts' task. After forty five minutes of each condition, participants proceeded to repeat the same ten-minute 3-back task previously completed before the fatiguing tasks.

Fatigue in Fitts' Tasks

A limited number of studies have investigated the effects of physical fatigue on Fitts' Law, employing maximal voluntary contractions (MVCs) in order to fatigue a neuromuscular plant (Missenard et al., 2009). These studies indicate differences in Fitts' Law due to fatigue. However, to the best of our knowledge, no studies have empirically validated the fatiguability of Fitts' Law alone. Understanding how task performance declines with repetitions of a Fitts' task will advance knowledge towards an understanding of the upper bounds on the law. That is, we intend to investigate if the relationship between difficulty and performance in Fitts' Law breaks down or shifts upwards in slope. To the best of our knowledge, no other study has examined the

interaction of cognitive and physical fatigue on Fitts' Law. Understanding the influence of each type of fatigue on the relationship between task difficulty and performance will help understand the mechanisms that each type of fatigue induce decrement through.

Phases in Reaching Movements

Woodworth's contributions led to the creation of the two-component model, a theory of goal-directed reaching that posits differences in control between movement phases (Elliott et al., 2001; Woodworth, 1899). Research has since established a primary phase for reaching movements consisting of ballistic submovements, and a secondary phase consisting of corrective submovements (Missenard et al., 2009; Pratt et al., 1994). These prior studies have clearly demonstrated differences in movement phases using participants' velocities, and we plan to incorporate these into our measures as well. There are conceptual differences between the two phases of a reaching movement, consisting of a distance-covering phase (primary phase) and homing-in phase (secondary phase). In Woodworth's two-component model, the primary phase begins through a force impulse, and the secondary phase demonstrates a visual feedback loop where participants visually correct their movements. Present research still supports this contention and has gone further to suggest a compromise between the primary phase and secondary phase for a given movement (Elliot et al., 2001; Elliot et al., 2010; Elliot et al., 2017; Meyer et al., 1988; Meyer et al., 1990). In Meyer's optimized submovement model, the speed-accuracy tradeoff coalesces into a tradeoff between the movement phases of reaching. Previous research has also accounted for several constraints in the speed-accuracy tradeoff, of which targets' distance and size is most relevant to our study (Fernandez & Bootsma, 2004; Thompson et al., 2007). Constraints of distance to a target (increasing distance) are referred to as effector

constraints, whilst constraints of target size (decreasing size) are referred to as task constraints. Effector constraints elicit higher peak velocities, while the shape of the velocity profile and duration of primary and secondary phases remain constant. Conversely, task constraints elicit lower peak velocities, while the duration of the secondary phase elongates relative to the primary phase. Conceptually, effector constraints emerge from limitations of an effector to cover a longer distance range, whilst task constraints emerge from limitations of visuo-motor corrections needed to accurately select a smaller target (Fernandez & Bootsma, 2004; Thompson et al., 2007).

CHAPTER 3: HYPOTHESIS DEVELOPMENT

3-Back Task

It is hypothesized that fatiguing task interventions will decrease performance on a 3-back task. We expect that cognitively demanding tasks (vigilance task and size constraints task) will contribute to decreases in 3-back performance more so than physically demanding tasks (arm contractions task and distance constraints task). However, we expect declines in 3-back performance across all fatiguing interventions. Specifically, we expect that accuracy will decrease from pre-test to post-test more in the cognitively demanding tasks, and that reaction time will increase from pre-test to post-test more in the cognitively demanding tasks.

Hypothesis 1: Accuracy will decrease from pre-test to post-test.

Hypothesis 2: Reaction time will increase from pre-test to post-test.

Hypothesis 3: Task type will moderate the relationship between pre-test and post-test accuracy and reaction time.

Fitts' Tasks

For the Fitts' measures, we suggest that constraint types will differentially impact performance in a later 3-back task. In the Fitts' tasks, increasing ID through task constraints and effector constraints will likely decrease MT in both cases. However, it is suggested that effector constraints will elicit a steeper MT slope and broader range than task constraints, due to the higher inertia forces (greater accelerations and decelerations) of primary-phase movements (Hoffmann, 2017). In traditional Fitts' designs where distance and size manipulations are

intermixed, the variance accounted for in MT seems to delegate size manipulations to narrower ranges, and distance manipulations to broader ranges.

Kinematics is used to quantify changes in movement that are caused by underlying forces (dynamics). The use of movement velocities and accelerations will reveal participants' physical performance in space-time with respect to the effector limb. Movement velocities indicate participants' speed throughout the arm-reaching motion, whilst movement accelerations infer participants' relative force throughout the motion as defined in Newton's second law of motion $F = ma$, where F denotes force acting on an object, m denotes mass of the object, and a denotes acceleration of the object. An object's acceleration is the first derivative of its velocity, which is the first derivative of its position in space. Previous limb aiming studies have distinguished differences in velocities between the primary and secondary phase (Thompson et al., 2007). The primary movement phase is largely ballistically guided, where an effector accelerates and decelerates towards a target. The secondary movement phase is largely visually controlled, where the effector homes in on the target while compensating for undershooting or overshooting the target. We suggest that movement accelerations will help to better understand the primary movement phase, where higher inertia forces are present than in the secondary movement phase (Hoffmann, 2017). We expect that increasing task constraints will decrease only secondary phase velocities and accelerations whilst increasing the duration of this phase, and that increasing effector constraints will increase only primary phase velocities and accelerations whilst increasing the duration of this phase (Schmidt et al., 1979). With longer distances, a greater force impulse is applied to the muscle – but the increase in force is generally not enough for the increase in distance, leading to an increase in the duration of the primary phase.

We suggest that workload from task constraints can be theorized to be more cognitively fatiguing, whereas workload from effector constraints can be theorized to be more physically fatiguing. Task constraints may decrease movement velocities and accelerations as a function of primarily mental workload from smaller target sizes, whereas effector constraints may decrease movement velocities and accelerations as a function of primarily physical workload from longer arm movements. In the 3-back tasks, we expect that fatigue from task constraints will decrease accuracy and increase reaction time more so than fatigue from effector constraints. These two Fitts' tasks are conjectured to be of higher visual-motor integration than the arm contractions and vigilance tasks.

Neuroimaging of Fatigue

Functional near-infrared spectroscopy (fNIRS) enables measurement of brain activity through hemodynamics (blood movement). As neural activity increases in brain regions through more synaptic transmission and action potentials, cerebral blood flow (CBF) increases to these regions to deliver more oxygen to energy-depleted neurons. Using near-infrared light, responses in oxygenated hemoglobin (HbO₂) and deoxygenated hemoglobin (HHb) chromophores can be imaged throughout the brain in real-time. Through this neuroimaging technique, we propose to quantify increases in brain activity related to task fatigue and performance. We expect that increasing task constraints will increase executive demand alongside decreases in target size. In accordance with previous literature, we propose that increased executive demand will primarily activate the prefrontal cortex (PFC) as task difficulty increases (Goto et al., 2011; Mehta & Parasuraman, 2013; Tajima et al., 2010). We also expect that increasing effector constraints will increase motor demand as larger arm muscles' movement is challenged alongside increases in

distance between targets. Previous literature (Dai et al., 2001; Liu et al., 2002; Mehta & Parasuraman, 2013) suggests increased motor demand will principally activate the primary motor cortex (M1) and supplementary motor area (SMA) as task difficulty increases. However, research has also indicated increased motor demand activates PFC (Dai et al., 2001; Goto et al., 2011; Liu et al., 2002, Pardini et al., 2013), where PFC seems to serve as a compensatory mechanism. We propose that increasing task constraints will increase activity in PFC more than effector constraints, as less emphasis is placed on physically demanding movements with shorter target distances, and more emphasis is placed on visual-cognitive functions with smaller target sizes. Furthermore, we hypothesize that the arm contractions task will more closely model the activity generated from the distance constraints task due to increased physical demand, whilst the vigilance task will more closely model the activity generated from the size constraints task due to increased cognitive demand. However, we also expect to see increases in activity in PFC across all tasks, in lieu of the aforementioned literature.

Hypothesis 4: All fatiguing tasks will increase functional compensation (HbO2) in PFC.

Hypothesis 5: Increasing task constraints will increase functional compensation (HbO2) in PFC more than effector constraints.

Hypothesis 6: The vigilance task will increase functional compensation (HbO2) in PFC more than the arm contractions task.

We suggest both task and effector constraints will increase activity in PFC, but effector constraints are likely to increase regional activation in M1 and SMA as well. Research has indicated that PFC is largely responsible for cognitive and motor control, and M1 and SMA are

largely responsible for gross motor control. However, analyses of M1 and SMA are beyond the scope of the present study.

CHAPTER 4: METHODOLOGY

Participants and Procedure

Forty participants were collected (24 females and 16 males), with a subset of 11 participants collected with our fNIRS system. Participants were recruited from the SONA system at UCF. Prerequisites for participation in this study included being from 18 to 25 years of age ($M = 18.40$, $SD = .59$), right handed, and with normal or corrected-to-normal visual acuity. Upon completion of the experiment, participants received SONA credits towards their psychology classes. All participants were treated according to the APA ethical and research guidelines. According to a G-Power analysis, with a 4×2 mixed factorial design, including an effect size of .25, standard alpha level (.05), and power level (.80), it was estimated that 48 participants would be needed to satisfy power requirements. In the present study, a 4×2 mixed factorial design was used consisting of testing period (pre-test 3-back versus post-test 3-back) as a within-participant variable, and fatiguing task intervention (size constraints task, distance constraints task, vigilance task, arm contractions task) as a between-participant variable (see Figure 1, Appendix A). A visual 3-Back task was used for the pre-test and post-test tasks and took participants approximately ten minutes to complete (see Figure 2, Appendix A). A standard visual search vigilance task (Temple et al., 2000) was used for the vigilance task and presented to participants for forty five minutes (see Figure 3, Appendix A). Participants were required to detect a target “O” versus a non-target forward-facing or backward-facing “D” continuously throughout the vigilance task (stimulus rate = 57.5 events per minute), wherein they only pressed the spacebar if a target was detected. In the arm contractions task, participants were instructed to lift either a 2lb, 5lb, or 10lb dumbbell for one minute on and thirty seconds off repeatedly until

forty five minutes was reached (see Figure 4, Appendix A). For the Fitts' tasks, participants were presented with a forty five minute task consisting of either long distances between targets (effector or distance constraints task; see Figure 5, Appendix A) or small target sizes (task or size constraints task; see Figure 6, Appendix A). Behavioral dependent variables included accuracy and reaction time during the 3-back tasks. Neural dependent variables included HbO₂ levels measured from PFC during the 3-back tasks. Participants were presented with a 3-back task, followed by one of the four fatiguing task interventions, and repeated the initial 3-back task.

Apparatus

The experiment was presented on a Dell Workstation running Windows 7 and a BenQ LED gaming monitor model XL2730Z (144Hz refresh rate, 2560 x 1440 resolution with 1ms response time). The 3-back and vigilance tasks were completed using a standard QWERTY keyboard (see Figure 7, Appendix A). The discrete aiming tasks were completed using a Wacom Intuos XL digitizing tablet (active area 488 × 305 mm) and pen stylus with a standard pen nib (see Figure 8, Appendix A). The tablet's interface was comprised of circular targets, and participants performed a discrete aiming task wherein they pointed towards a cued target with the stylus. NeuroScript MovAlyzeR software was used to present stimuli. The Index of Difficulty was 5.64 bits for the size constraints task (target width = .4 cm, target amplitude = 10 cm) and 4.39 bits for the distance constraints task (target width = 4 cm, target amplitude = 42 cm).

fNIRS Data Acquisition

Functional near-infrared spectroscopy (fNIRS) measurements of HbO₂ and HHb were recorded using a 20-channel NIRSport 88 NIRx imaging system (NIRx Medical Technology,

New York; see Figure 1, Appendix B). Participants were fitted with a cap consisting of 16 optodes, including 8 source optodes and 8 detector optodes (see Figure 2, Appendix B). Recording optodes were placed over the prefrontal cortex, with a total of 8 source optodes and 7 detector optodes used (see Figure 3, Appendix B). Statistical analyses were performed in nirsLAB, and topographical measures of brain activity were analyzed.

fNIRS Preprocessing Procedures

Data were acquired at a sampling rate of 7.8 Hz using two wavelengths of light (850nm and 760nm) to measure HbO₂ and HHb levels. Optodes were configured according to the international 10-20 system and used a 3cm long source-detector separation using plastic spacers. Data were preprocessed using a band-pass filter of .01 to .09 Hz in order to remove physiological noise (Mayer wave artifacts (0.1 Hz), respiratory activity (0.3 Hz), cardiac cycles (1 Hz)) and motion artifacts (Stefanovska, 2007). Discontinuities were removed (STD threshold = 5), and spike artifacts were interpolated using the nearest signals (STD threshold = 5). Optical Density data were converted into concentration changes using the modified Beer-Lambert Law (Cope & Delpy, 1988; Delpy et al., 1988). Afterwards, all trials of the same stimulus type were block-averaged, producing two mean hemodynamic response signals (pre-test versus post-test) for each channel and participant.

CHAPTER 5: RESULTS

Behavioral Results

Results showed a significant main effect of testing period on accuracy for targets $F(1, 38) = 20.44, p < .001, \eta^2 = .36$ (see Figure 1, Appendix C). This indicated that participants were significantly more accurate at detecting targets after completing the fatiguing tasks ($M = 80\%$, $SE = 2\%$) versus before completing the fatiguing tasks ($M = 72\%$, $SE = 2\%$). However, there was no significant main effect of fatiguing task type or interaction between testing period and fatiguing task type on accuracy for targets.

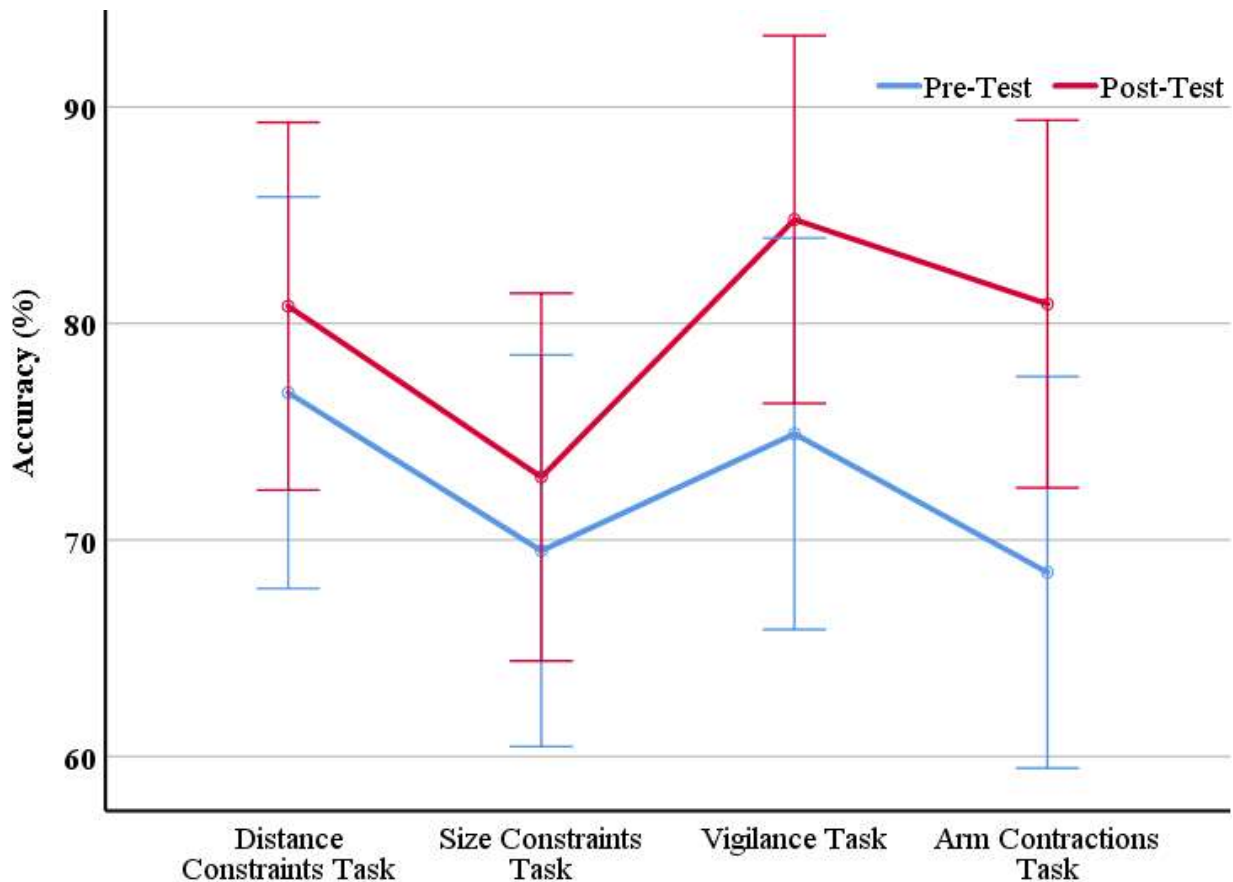


Figure 1: Pre- to Post-Test Differences in 3-Back Accuracy for Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

Results also showed a significant main effect of testing period on accuracy for non-targets $F(1, 38) = 7.02, p < .05, \eta^2 = .16$ (see Figure 2, Appendix C). This indicated that participants were significantly more accurate at detecting non-targets after completing the fatiguing tasks ($M = 89\%, SE = 1\%$) versus before completing the fatiguing tasks ($M = 82\%, SE = 2\%$). However, there was no significant main effect of fatiguing task type on accuracy for non-targets.

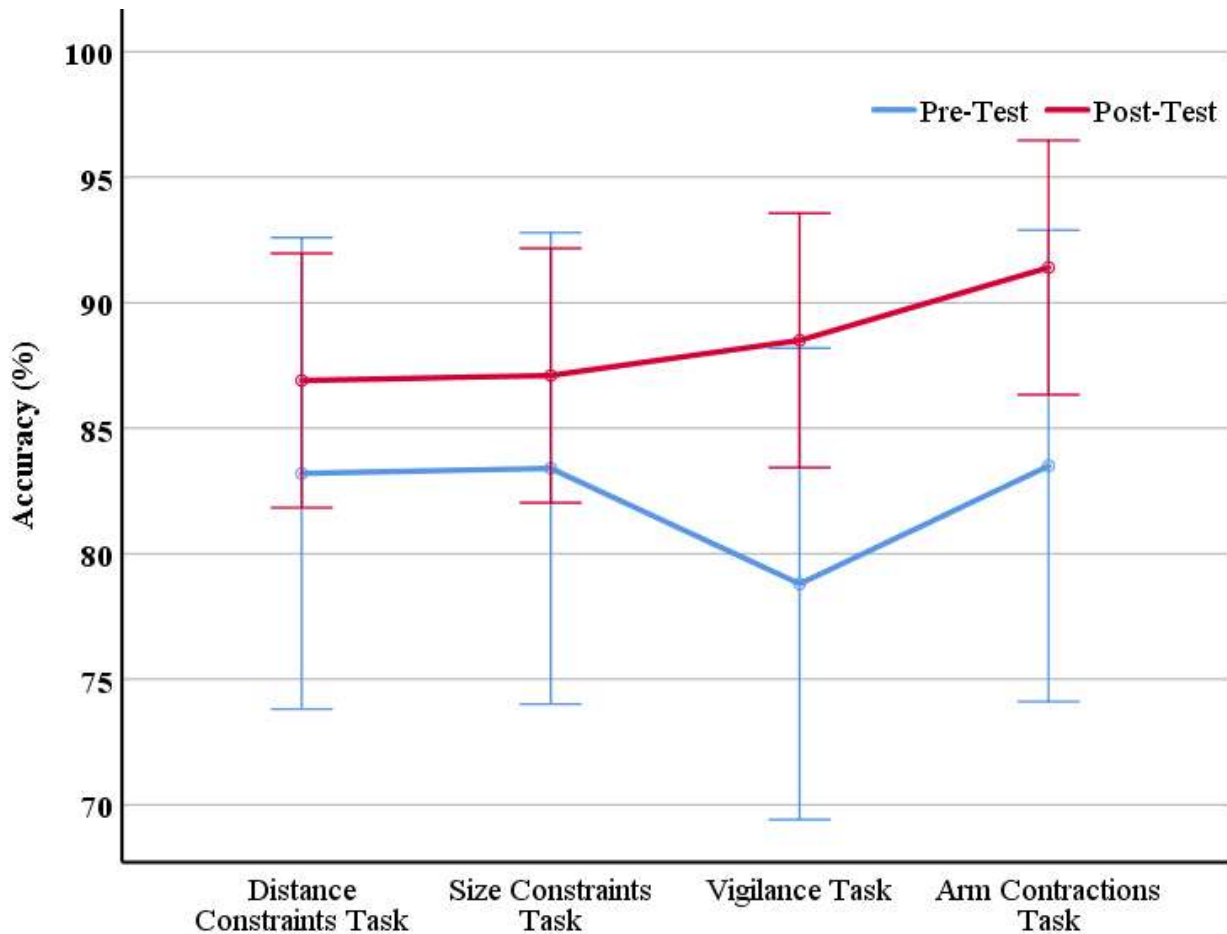


Figure 2: Pre- to Post-Test Differences in 3-Back Accuracy for Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

Results showed a significant main effect of testing period on reaction time for targets $F(1, 38) = 7.31, p < .05, \eta^2 = .17$ (See Figure 3, Appendix C). This indicated that participants were significantly faster at detecting targets after completing the fatiguing tasks ($M = 838.43$ ms, $SE = 48.6$) versus before completing the fatiguing tasks ($M = 917.09$ ms, $SE = 45.14$ ms).

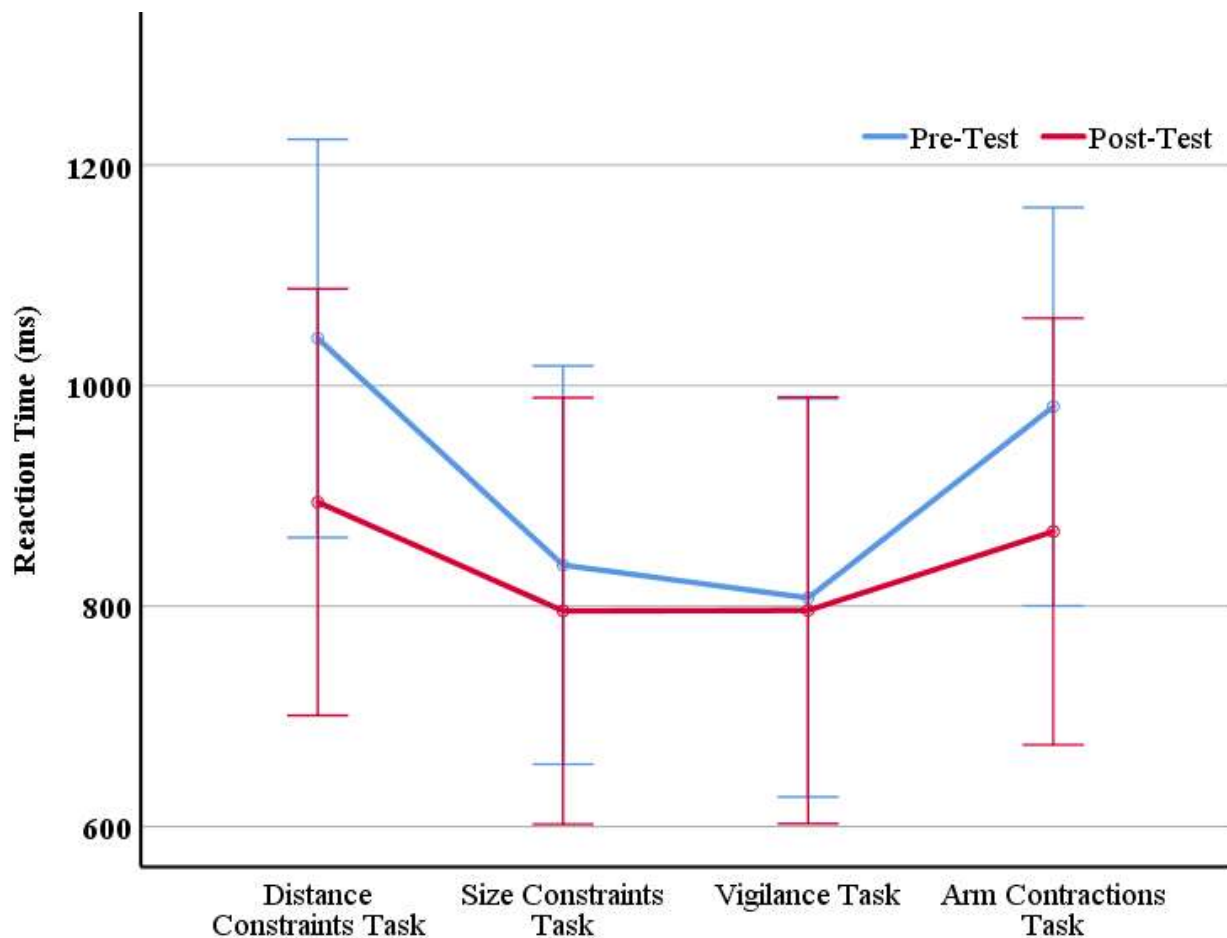


Figure 3: Pre- to Post-Test Differences in 3-Back Reaction Time for Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

However, there was no significant main effect of fatiguing task type or interaction between testing period and fatiguing task type on reaction time for non-targets (see Figure 4,

Appendix C). Furthermore, results did not show a main effect of testing period, fatiguing task type, nor interaction between testing period and fatiguing task type on reaction time for non-targets.

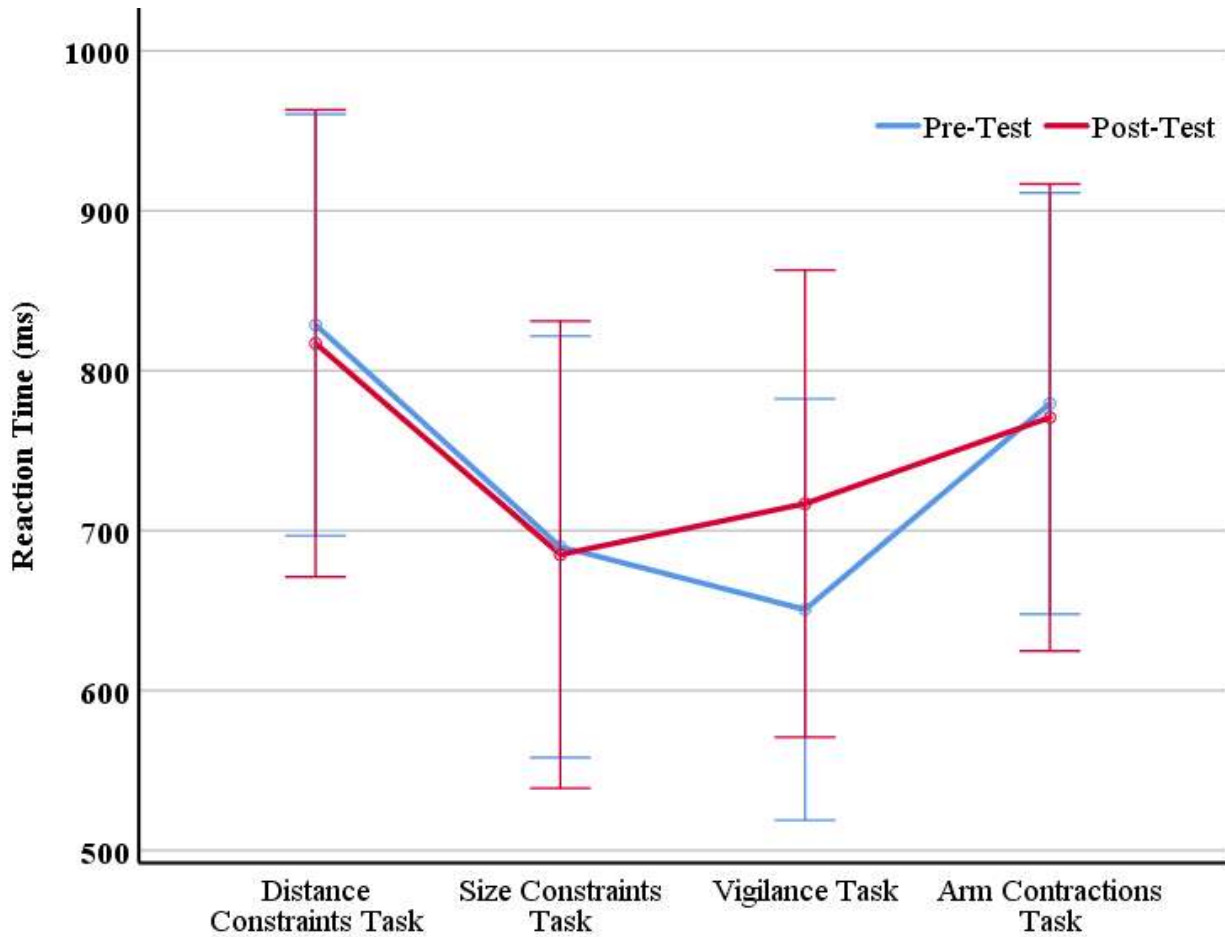


Figure 4: Pre- to Post-Test Differences in 3-Back Reaction Time for Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

Standardized change scores were computed between pre-test and post-test periods for participants' accuracy and reaction times collapsed across target types. Results did not show a

main effect of target type, fatiguing task type, nor interaction between target type and fatiguing task type on participants' accuracy (see Figure 5, Appendix C).

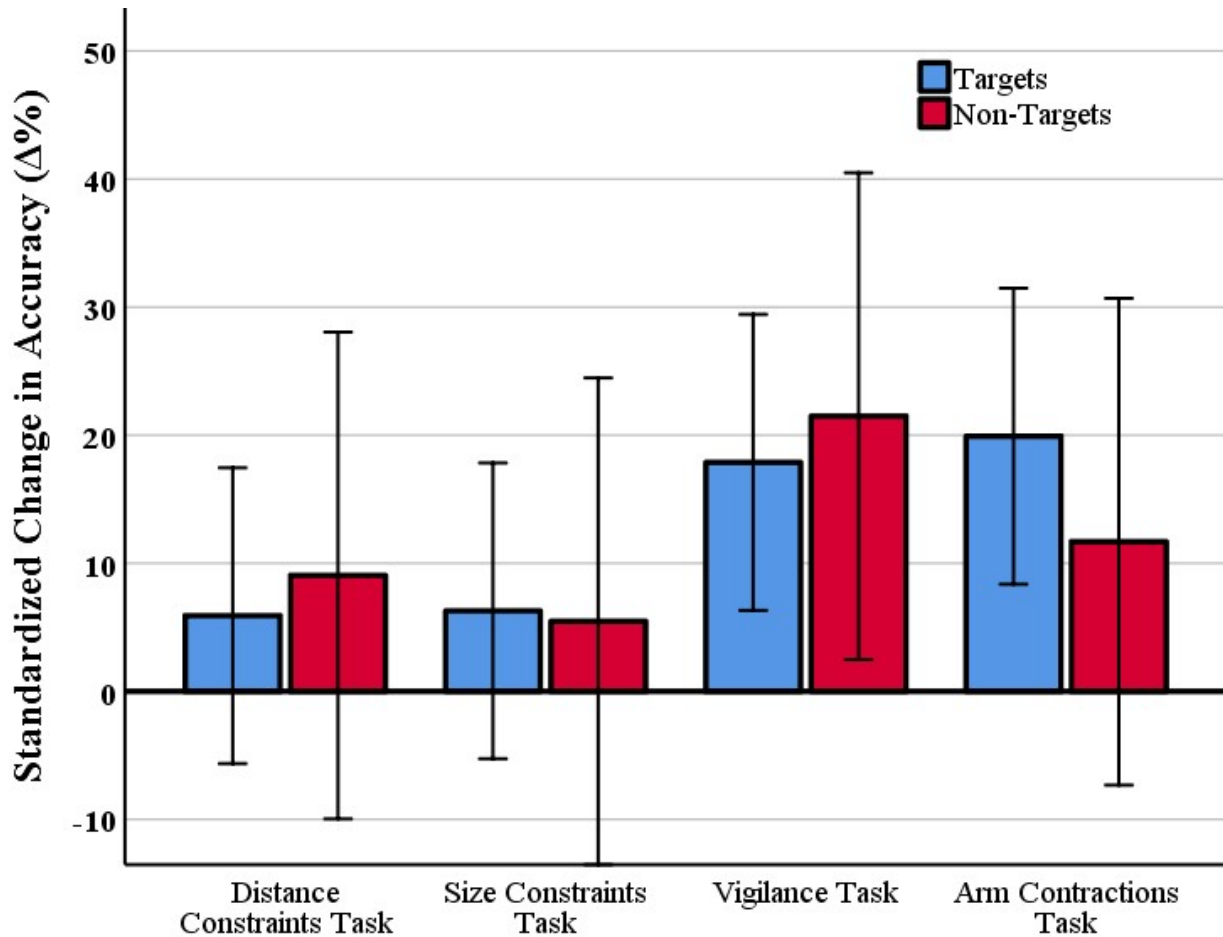


Figure 5: Pre- to Post-Test Standardized Changes in 3-Back Accuracy for Targets vs Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

However, results showed a main effect of target type on the change in reaction time from pre-test to post-test $F(1, 38) = 8.31, p < .01, \eta^2 = .19$. This indicated that participants had greater decreases in reaction time after the fatiguing tasks for non-targets ($M = -7\%, SE = 3\%$) versus greater increases in reaction time after the fatiguing tasks for targets ($M = 4\%, SE = 4\%$) after the

fatiguing tasks. Furthermore, significant differences were identified between the vigilance and distance constraints tasks ($p < .05$), with the vigilance task leading to the greatest increases in 3-back reaction time ($M = 16\%$, $SE = 7\%$) and the distance constraints task leading to the greatest decreases in 3-back reaction time ($M = -15\%$, $SE = 6\%$) (see Figure 6, Appendix C).

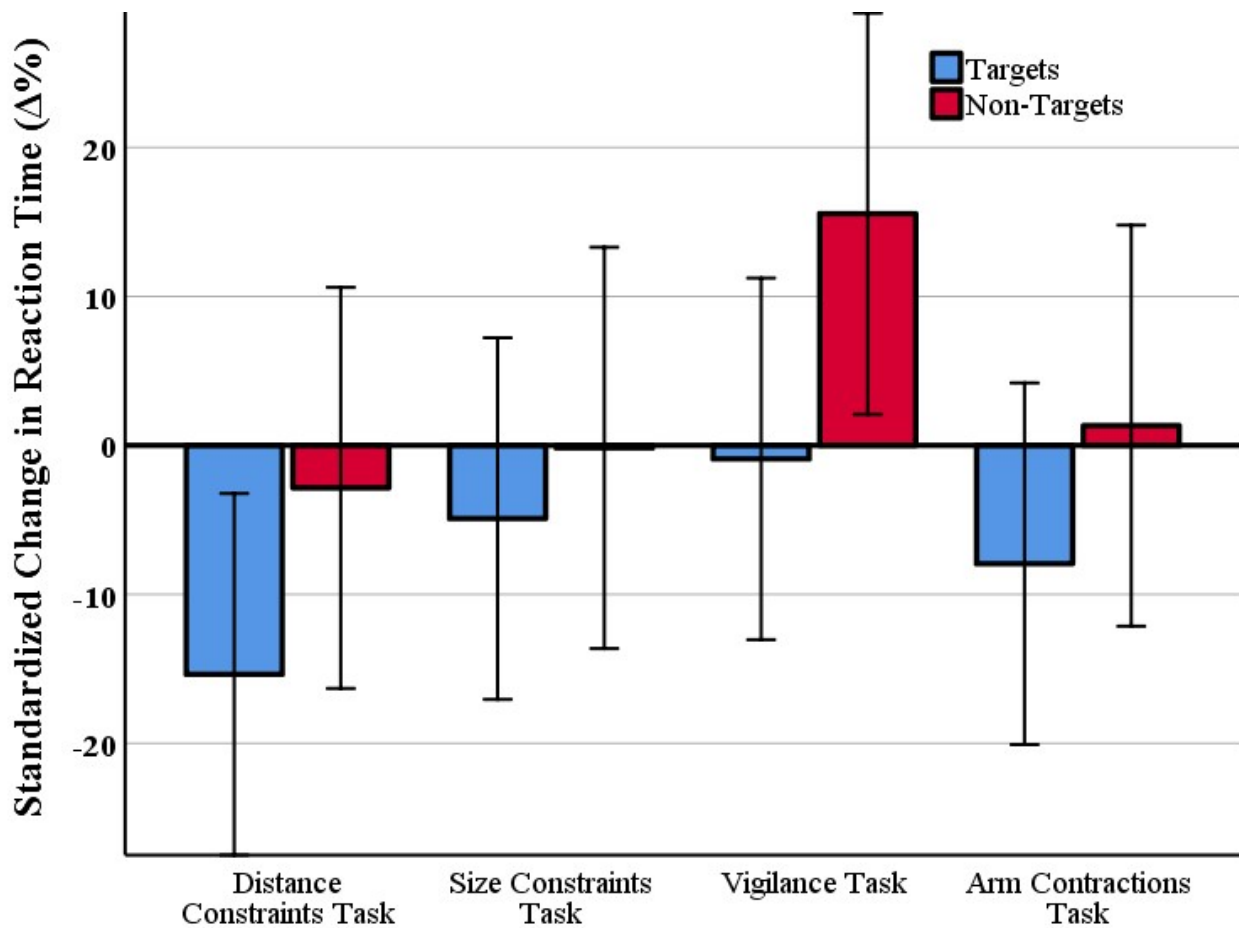


Figure 6: Pre- to Post-Test Standardized Changes in 3-Back Reaction Time for Targets vs Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

Neuroimaging Results

Changes in 3-back HbO2 levels after the fatiguing tasks were thresholded in nirsLAB using statistical parametric mapping (SPM) F-tests. Seven F-contrasts were taken across 20 channels x 2 testing periods x 11 participants, consisting of a test of main effects for all participants from pre-test to post-test, and six comparisons between all combinations of fatiguing tasks. Results indicated significant increases in HbO2 levels at Channel 5 ($F(3, 9) = 11.9, p < .05$) and Channel 12 ($F(3, 9) = 6.96, p < .05$) in a 3-back task when collapsed across all fatiguing tasks (see Figure 7, Appendix C). This suggests that activity in PFC increases during a 3-back task after exposure to all our fatiguing task interventions, regardless of fatigue type.

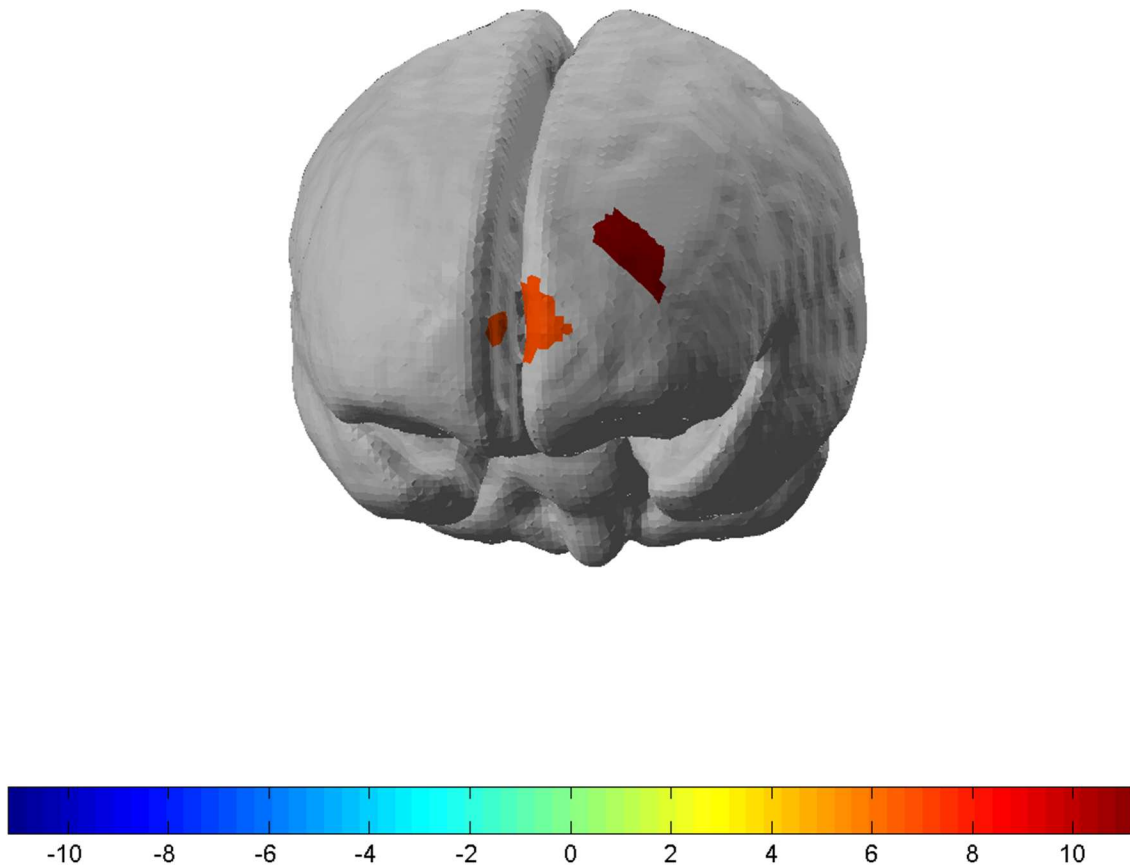


Figure 7: F-Map for Pre- to Post-Test Increases in 3-Back HbO2 Levels After All Fatiguing Tasks at Channel 5 (dlPFC) and Channel 12 (dmPFC). $N = 11$.

Furthermore, results indicated a significant interaction F-contrast between fatiguing task type and testing period at Channel 9 ($F(1, 4) = 9.74, p < .05$) and Channel 14 ($F(1, 4) = 9.62, p < .05$) for higher HbO₂ levels after the size constraints task, versus the distance constraints task (see Figure 8, Appendix C). This suggests that increases in activity in PFC are greater during a 3-back task after manipulating target size rather than distance in a prior fatiguing Fitts' task. However, no other differences in brain activity were observed between fatiguing task groups.

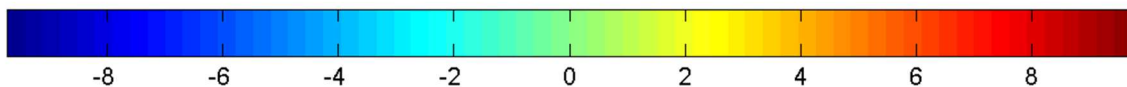
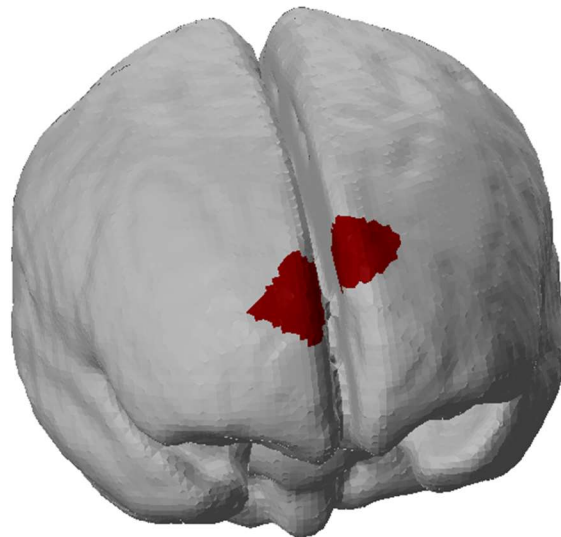


Figure 8: F-Map for Pre- to Post-Test Increases in 3-Back HbO₂ Levels for Size Constraints Task versus Distance Constraints Task at Channel 9 (dmPFC) and Channel 14 (dmPFC). $N = 6$.

Importantly, none of the tests reported here survived Bonferroni corrections at the $p < .0025$ level (accounting for multiple corrections across 20 channels). As such, the neuroimaging results here are taken with a grain of caution.

CHAPTER 6: DISCUSSION

The 3-back task used here is purposed to analyze participants' WMC, regarded as the flexibility with which one can manipulate information short-term. Participants improved in accuracy and reaction time after completing all fatiguing tasks, rather than declining in performance as hypothesized. This reflects the complex and multidimensional nature of fatigue, such that some demanding tasks may improve rather than decrease performance as a function of arousal. With optimal levels of arousal, task performance may not be inhibited and may even be stimulated depending on tasks' context and interactions. Whilst a bevy of research is available on the vigilance decrement, emerging studies have examined or reviewed the potential "vigilance increment," or increase in performance while maintaining vigilance (Al-Shargie et al, 2019). A number of studies have examined vigilance increment through cognitive enhancement techniques, which can range from physical exercise (Lambourne & Tomporowski, 2010) to mental exercise (Lutz et al., 2009). Many of these cognitive enhancement techniques pose contradictory findings, likely owing to context-specific interactions between tasks and individual differences in vigilance monitoring. The present thesis seems to have demonstrated mostly vigilance increment effects, rather than the traditional vigilance decrement.

The fatiguing tasks in the present study may have facilitated increased cognitive functions from pre-test to post-test 3-back – a finding which seems supported by the increases in PFC activity across all task conditions. Interestingly, the greatest increases in 3-back reaction time came after the vigilance task, possibly alluding to the similar nature of the vigilance task and 3-back tasks, where participants need to attend to targets versus non-targets. Furthermore, the greatest decreases in 3-back reaction time came after administration of the distance

constraints task, which may allude to our suggestion that the distance constraints task is less cognitively demanding and more physically demanding. Alternatively, these results may also be in part due to testing effects – as participants drastically improved in accuracy and reaction time from pre-test to post-test. However, participants first engaged in up to three practice trials to achieve at least 70% baseline accuracy before continuing to the pre-test 3-back task. This was chosen in order to minimize fatigue before the experimental manipulations but also allow participants to improve their accuracy beyond chance in cases where participants scored 50% or less on the practice trials. Furthermore, the pre-test and post-test tasks were separated by 45 minutes of a cognitively and/or physically demanding task, rather than continuously repeating the 3-back task in search of traditional vigilance decrement. We suggest that the effects reported here are related to compensatory increases in fatigue-related brain activity, as wholesale increases in 3-back task performance were matched by task-wide increases in brain activity in dorsomedial prefrontal cortex (dmPFC) and dorsolateral prefrontal cortex (dlPFC). These two regions are implicated in executive function, and compensatory activity in dlPFC has been reported before in the cognitive fatigue literature (Causse et al., 2017; Mehta & Parasuraman, 2013). However, further analyses such as brain-behavioral regressions are necessary to elucidate the potential compensatory neural mechanisms underlying our sample here.

Intriguingly, the size and distance constraints groups differed in brain activity from pre-test to post-test 3-back tasks, in accordance with our hypotheses. The size constraints task elicited significantly higher brain activity in dmPFC during the post-test 3-back task compared to the distance constraints task, supporting our prediction that size constraints in Fitts' Law elicit more cognitive demand than physical demand, as opposed to distance constraints which we

suggest elicit more physical demand than cognitive demand. The neural correlates of size versus distance constraints have yet to be empirically analyzed, to the best of our knowledge, and elucidating the cognitive role in Fitts' Law can help shed light on different forms of goal-directed arm movements (e.g., writing, pointing with a mouse). The present thesis marks the first study to empirically examine these neural correlates and shines an exploratory light on the fundamental central contributors to Fitts' Law and its two primary components (Fitts, 1954; Elliot et al., 2010; Bohan et al., 2005). However, future studies should examine both PFC and other areas related to motor demand such as primary motor cortex (M1) and supplementary motor area (SMA) in tandem, in order to test for potential double dissociations between cognitive and physical demand. Fitts' Law has been rigorously tested to model visual-motor performance since its inception more than 60 years ago (Fitts, 1954). However, it has yet to been purposed to reverse-engineer the separability and integration of these visual-motor mechanisms in the brain, for which this thesis hopes to provide fundamental research untoward this critical goal. The separability of mind and body is an ode to the original questions by Descartes on duality (Descartes, 1637), for which the mechanisms of fatigue domains in conjunction with Fitts' constraint types may assist in scientifically testing this distinction.

The present thesis has a variety of theoretical implications for the scientific literature on fatigue. Understanding the effects of fatigue on executive function using a domain-wide approach may help to set the boundaries on different types of fatigue. This study contributes to the explanation of different domains of fatigue through both peripheral and central factors, where only one other study has done so (Mehta & Parasuraman, 2013). Furthermore, this study adds to the literature by empirically examining cognitively and physically fatiguing task domains

through different levels of visual-motor integration, which serves to elucidate theoretical levels of integration in the mind-body distinction. Importantly, our findings extend the nature of increment versus decrement in cognitive-physical fatigue interactions, which may help to transform fatiguing effects into restorative effects in cognitive and physical vigilance tasks. This study extends previous research on fatigue to tasks with high levels of visual-motor integration (e.g., the size constraints and distance constraints tasks), which may serve as more realistic approximators for everyday tasks that are not confined to largely cognitively versus physically demanding tasks. Whilst tasks with low levels of visual-motor integration (e.g., the vigilance versus arm contractions tasks) fundamentally distinguish between cognitive versus physical fatigue, understanding the continuum of visual-motor integration may be crucial to generalizing empirical studies of fatigue to everyday life.

The present study has theoretical implications for the design considerations of brain-computer interfaces (BCIs). Fatigue may be an important consideration in neuroadaptive interfaces, where changes in mental states are used to switch between levels of automation (and thus human operators' roles) in an automated agent such as a self-driving car. The Yerkes-Dodson Law explains that an equilibrium between high and low arousal leads to optimal performance (Yerkes & Dodson, 1908). Future research should aim to develop neuroadaptive interfaces that consider changes in mental states by fatiguing domain (including measurements of PFC, M1, and SMA activity among other task domain-dependent regions) and level of visual-motor integration (including the functional and effective connectivity between these brain regions alongside activation). Applying this type of neuroadaptive automation to autonomous vehicles such as unmanned automobiles may eventually help prevent the loss of human lives, as

the primary cause of countless accidents is human complacency in error and situation monitoring (Greenlee, DeLucia, & Newton, 2018). Conversely, in manual vehicle operations neuroadaptive automation may mitigate accidents caused by human fatigue (Bener, Yildirim, Özkan, & Lajunen, 2017). Further research is needed to determine how these two issues may be better resolved by integrating humans and machines using BCIs. Importantly, investigating these changes in arousal and fatigue based on a task's domain and level of visual-motor integration may help to optimize human effectiveness, efficiency, and safety using these interfaces.

The present thesis has various practical implications within the realm of human-machine interaction. These fatiguing tasks map onto high-risk scenarios in transportation, such as operation of automobiles, ships, or aircraft. Furthermore, mitigating fatigue and maintaining performance is critical for surgical operators engaging in vigilance and reaching movements with specialized tools (e.g., suturing and laparoscopy). Fatigue can be perilous in these situations and is usually accompanied by performance decrement, where the safety, efficiency, and effectiveness of operations become compromised. However, in some cases performance increment occurs, and methods to maximize this enhancement should be the one of the focuses of fatigue studies going forward. In understanding how we can mitigate and even reverse fatigue, we stand at better odds to decrease the prevalence of fatal accidents related to human error in the realm of human-machine interaction. These tasks may be purposed as tests to use in of training or selection batteries for physical and cognitive aptitudes for a variety of operational disciplines such as unmanned aerial vehicle (UAV) or air traffic controller selection and training, teleoperation and robotic surgery, among countless others.

Appendix A – Task Measures.

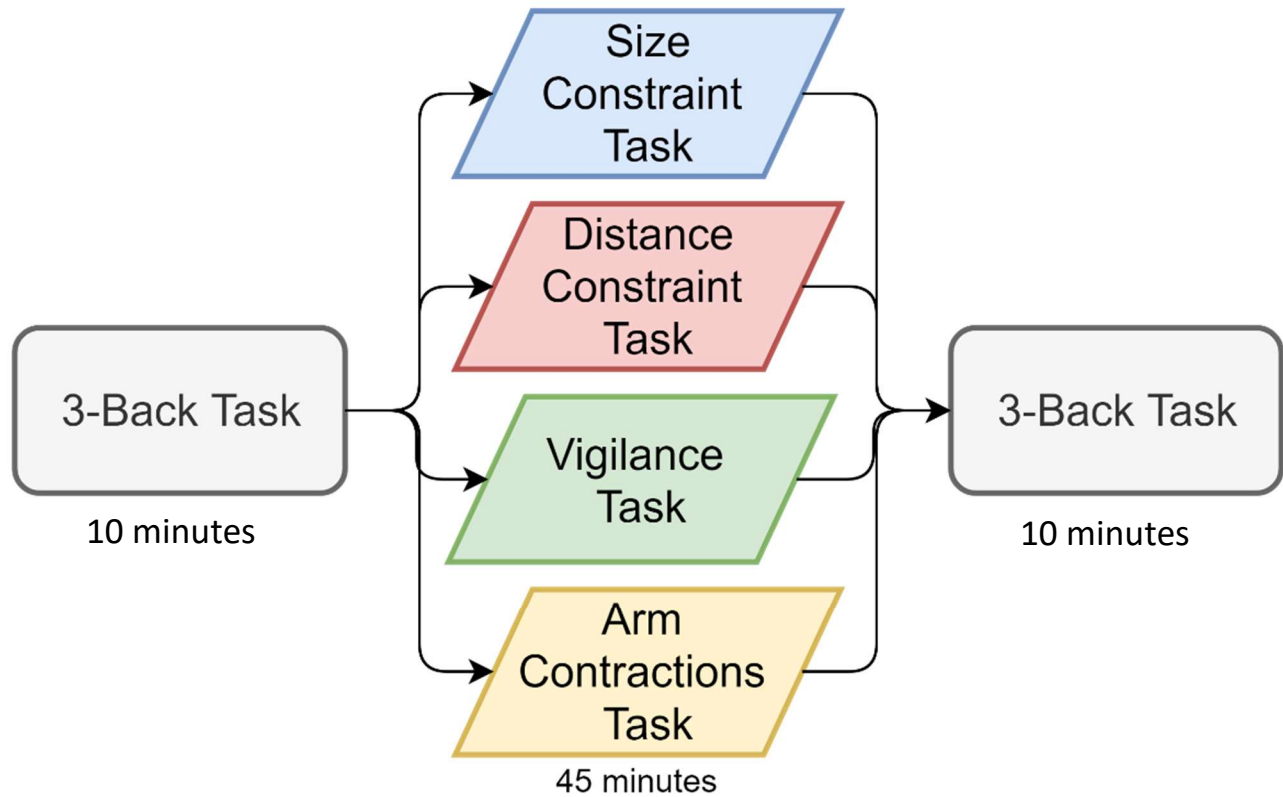


Figure 1: 4x2 Experimental Design and Procedures

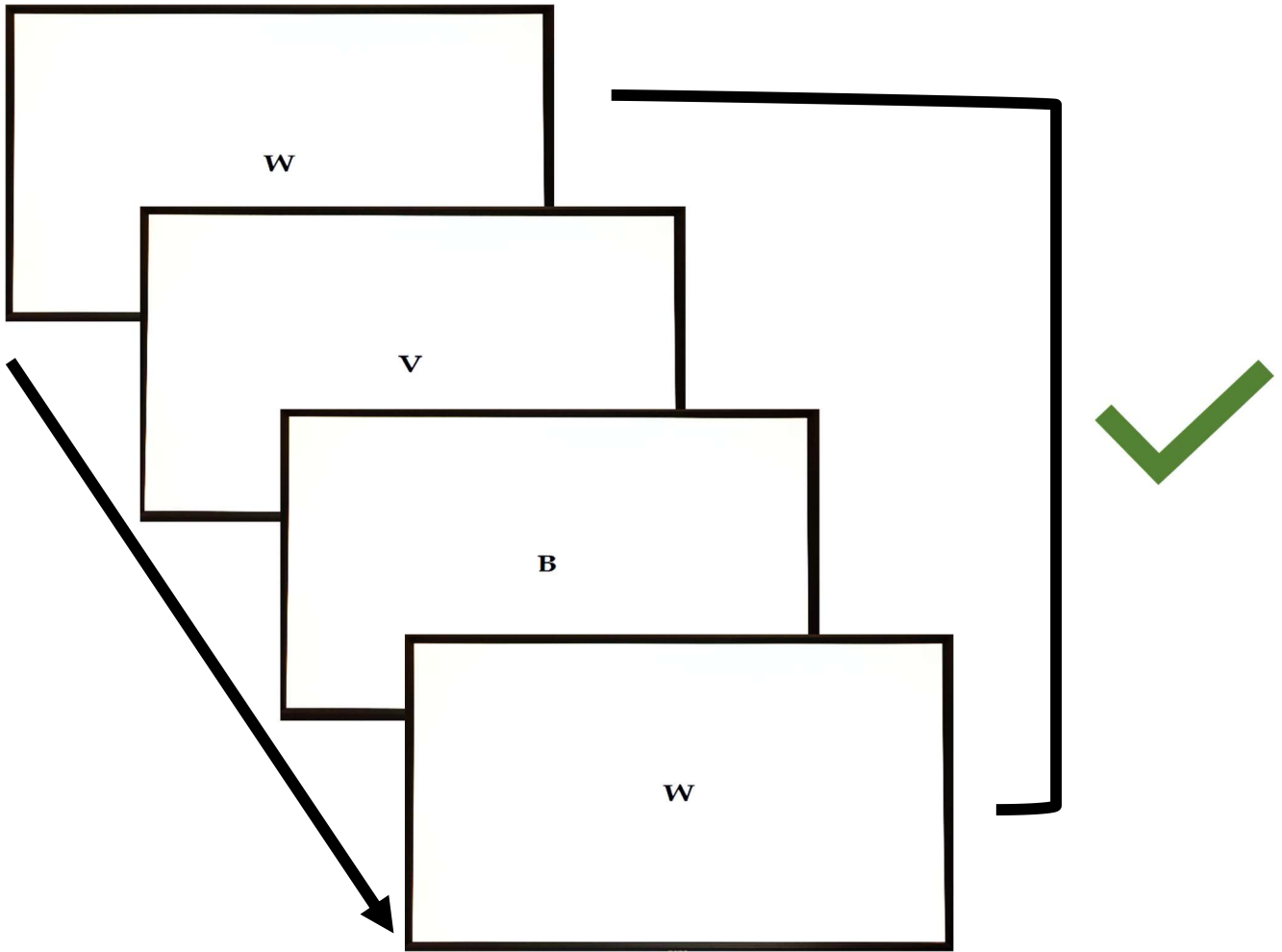


Figure 2: 3-Back Task Procedure

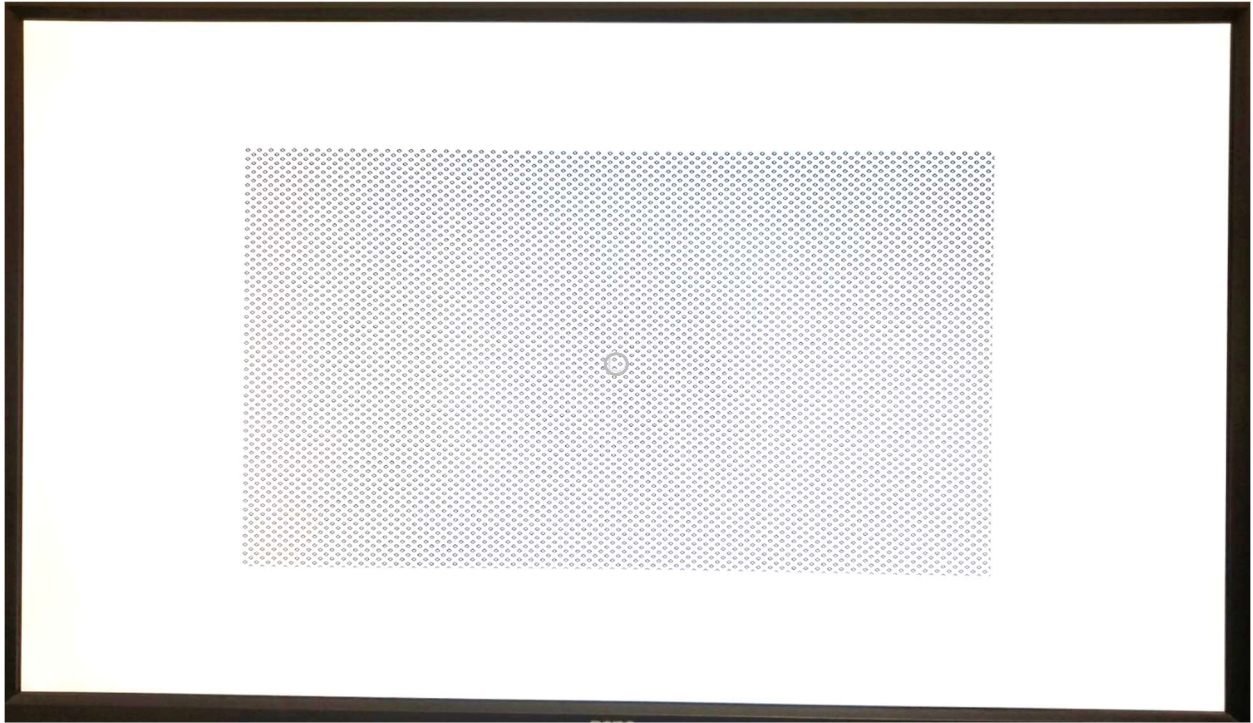


Figure 3: Vigilance Task



Figure 4: Arm Contractions Task (Researcher Self-Depicted)

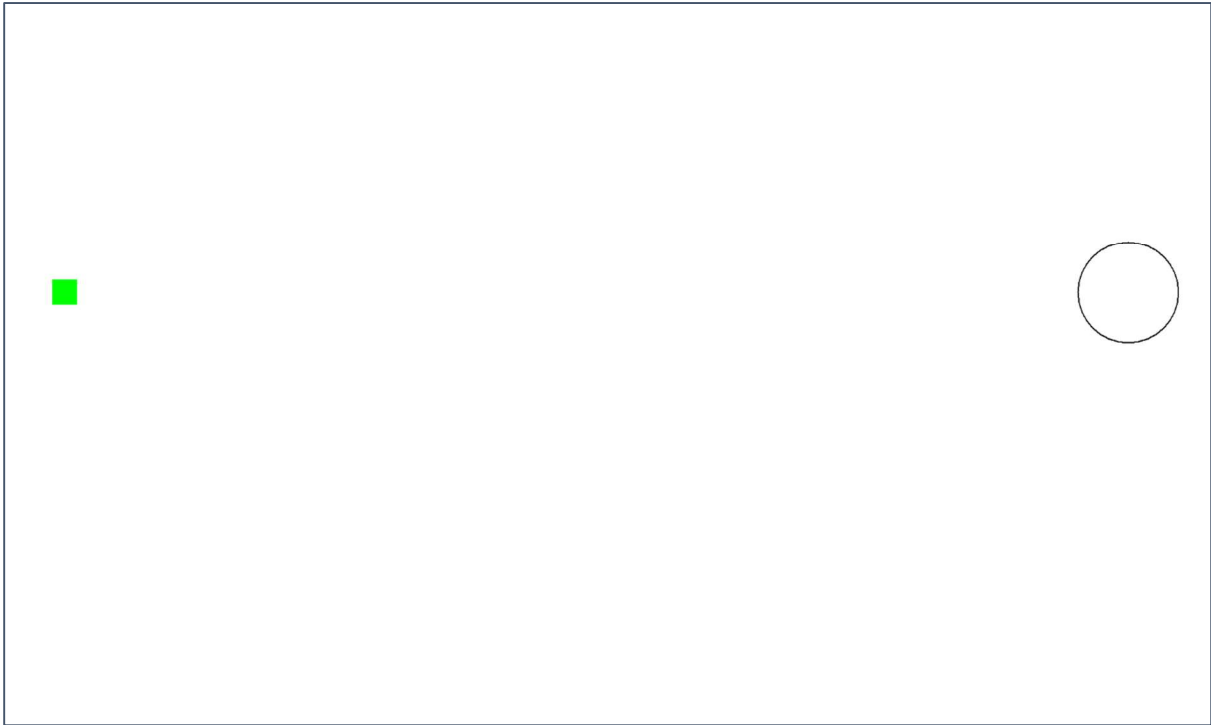


Figure 5: Distance Constraints Task (Index of Difficulty = 16 Bits)

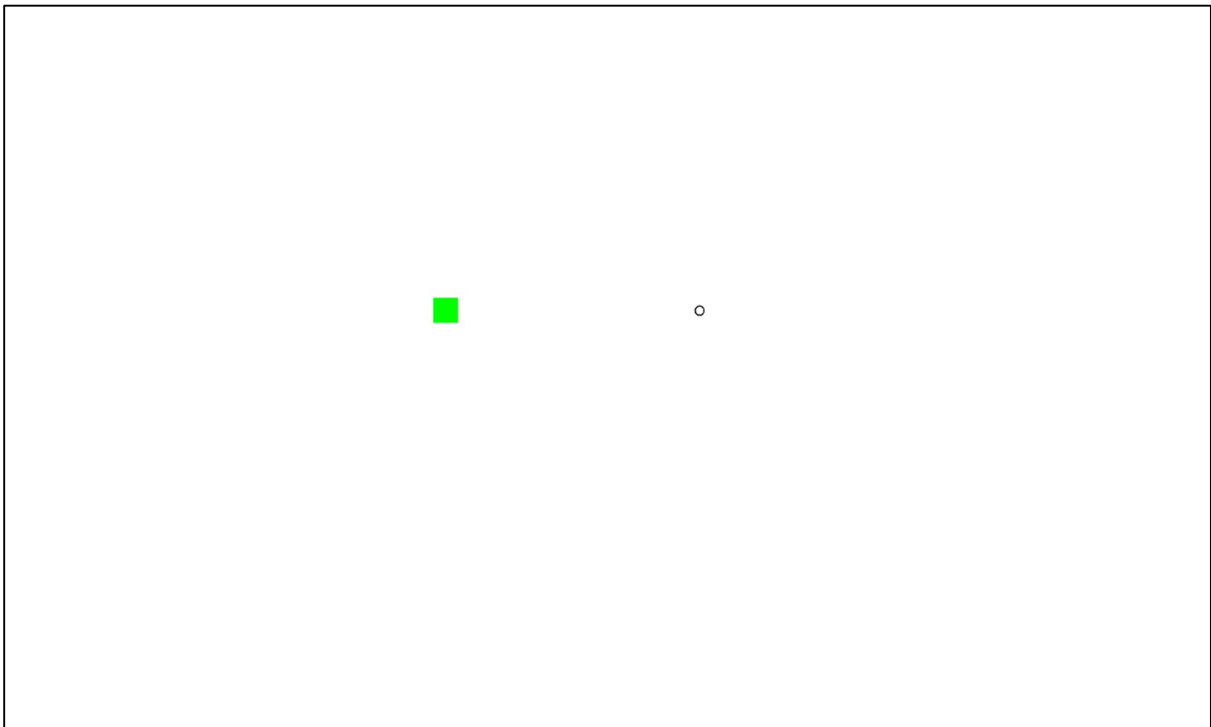


Figure 6: Size Constraints Task (Index of Difficulty = 16 Bits)

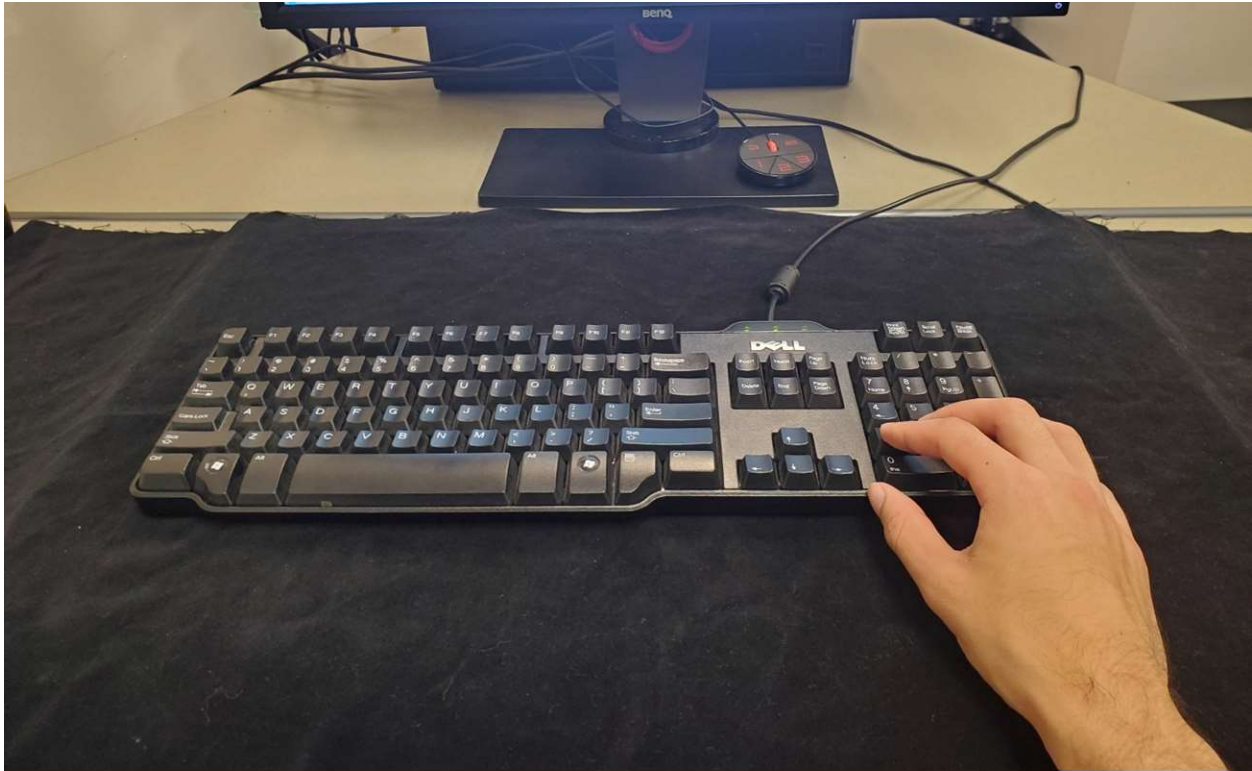


Figure 7: Standard QWERTY Dell Keyboard

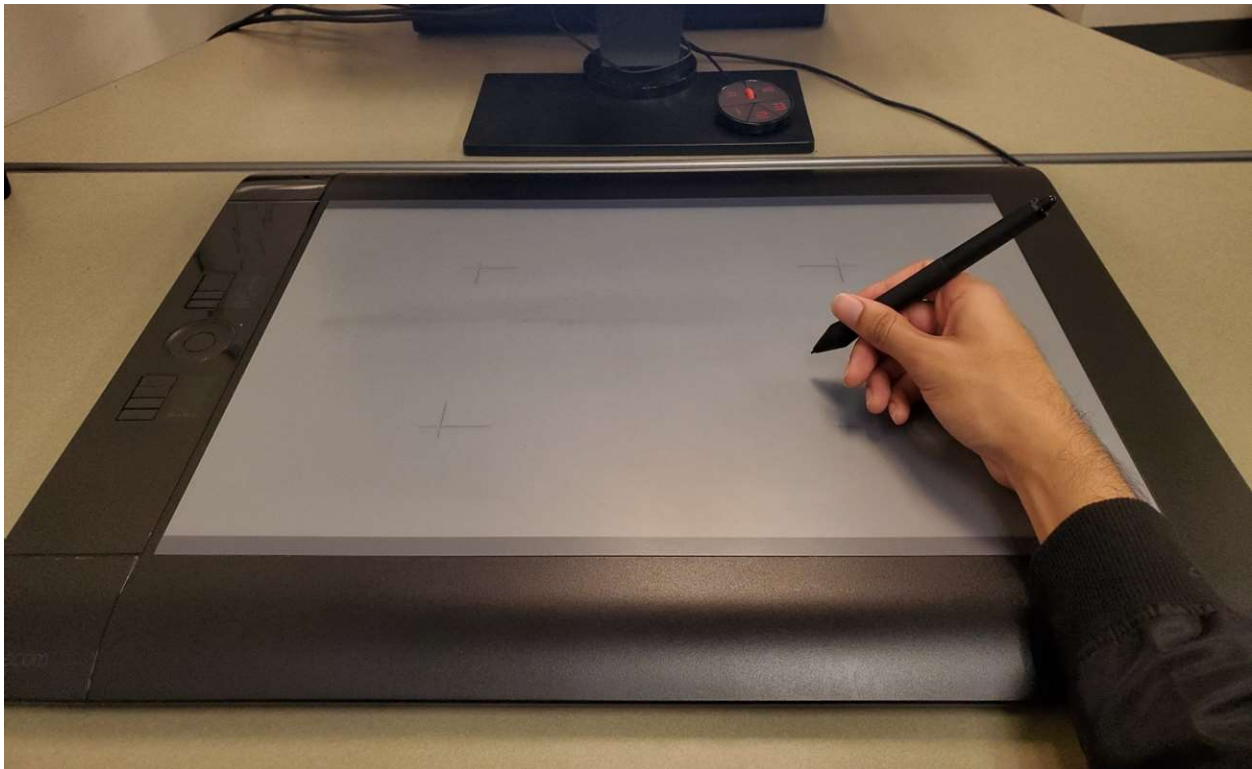


Figure 8: Wacom Intuos XL Digitizing Tablet (488×305 mm) and Pen Stylus

Appendix B – Brain Imaging Equipment and Software.

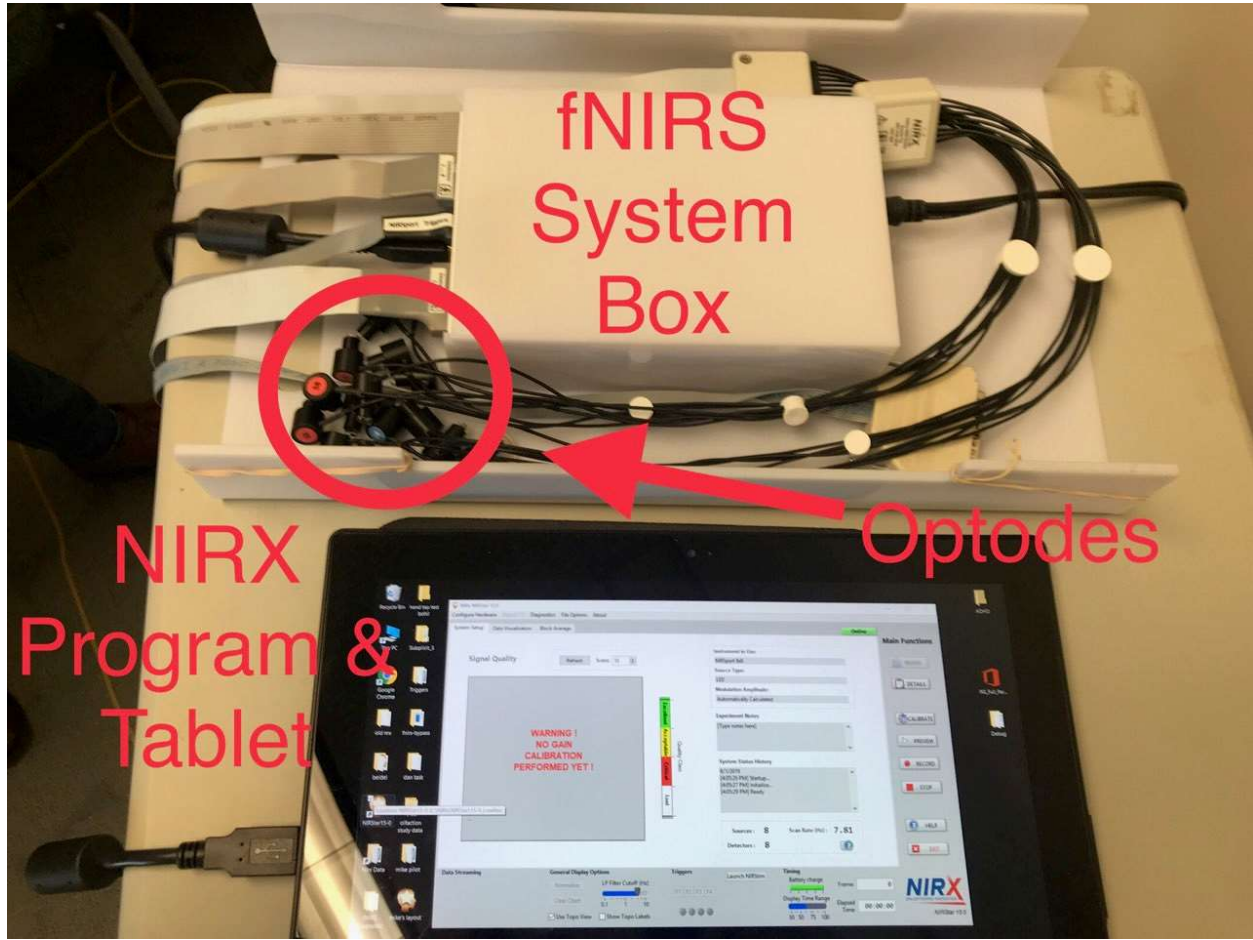


Figure 1: 20-channel NIRx fNIRS System

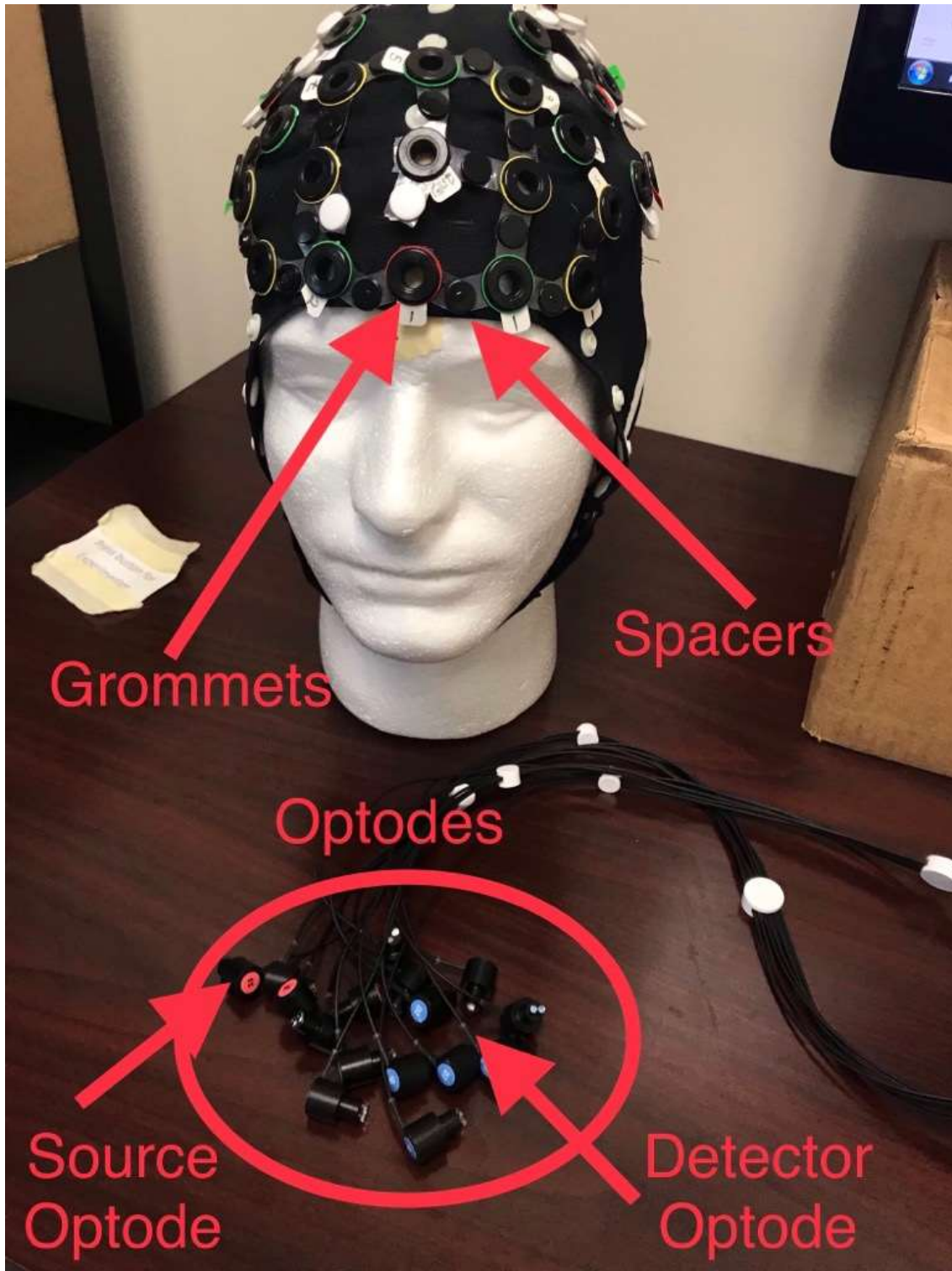


Figure 2: 20-channel NIRx fNIRS Cap and Optodes

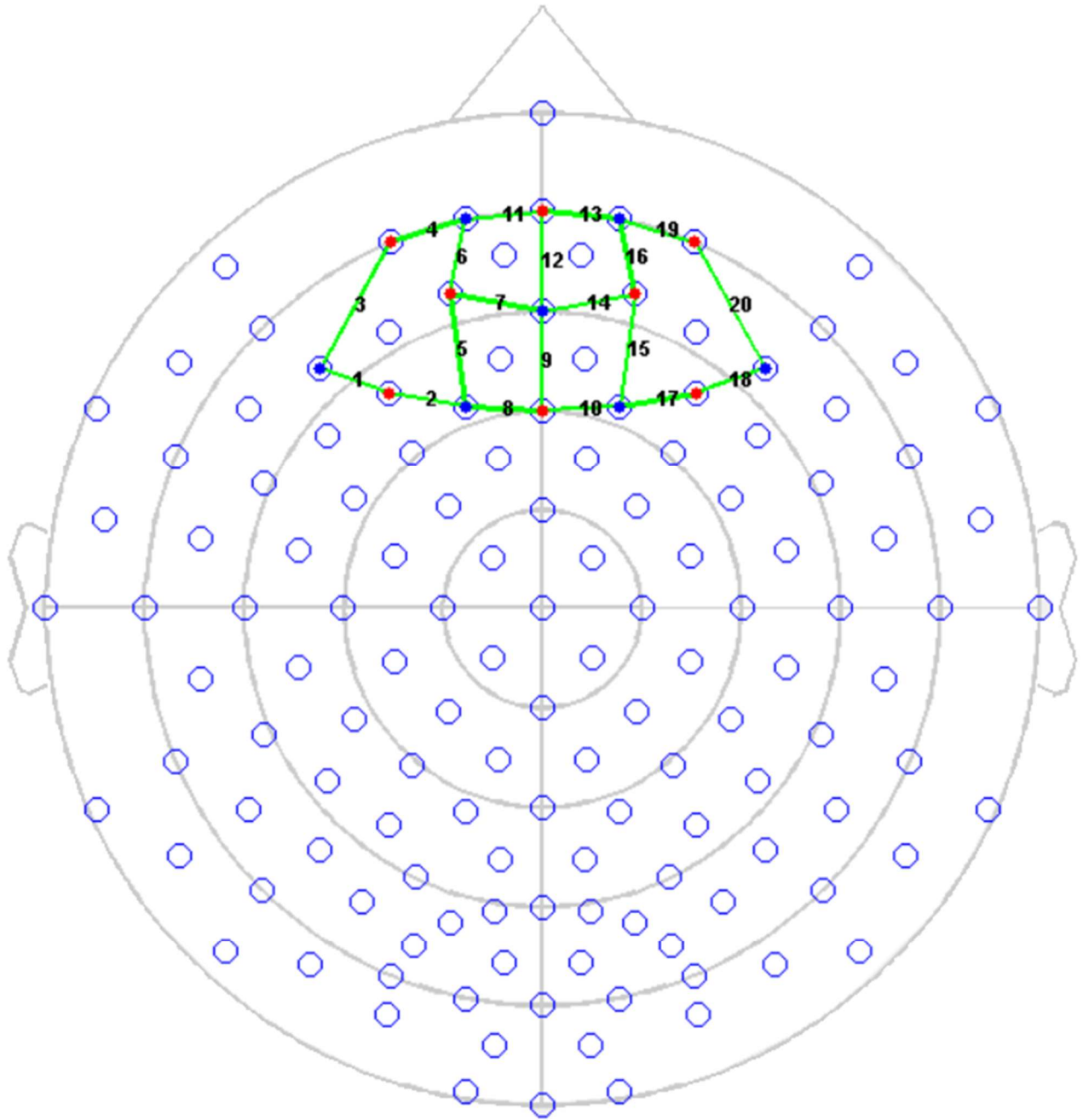


Figure 3: 10-20 Prefrontal Cortex Probe Layout

Appendix C – Behavioral and Neuroimaging Graphs.

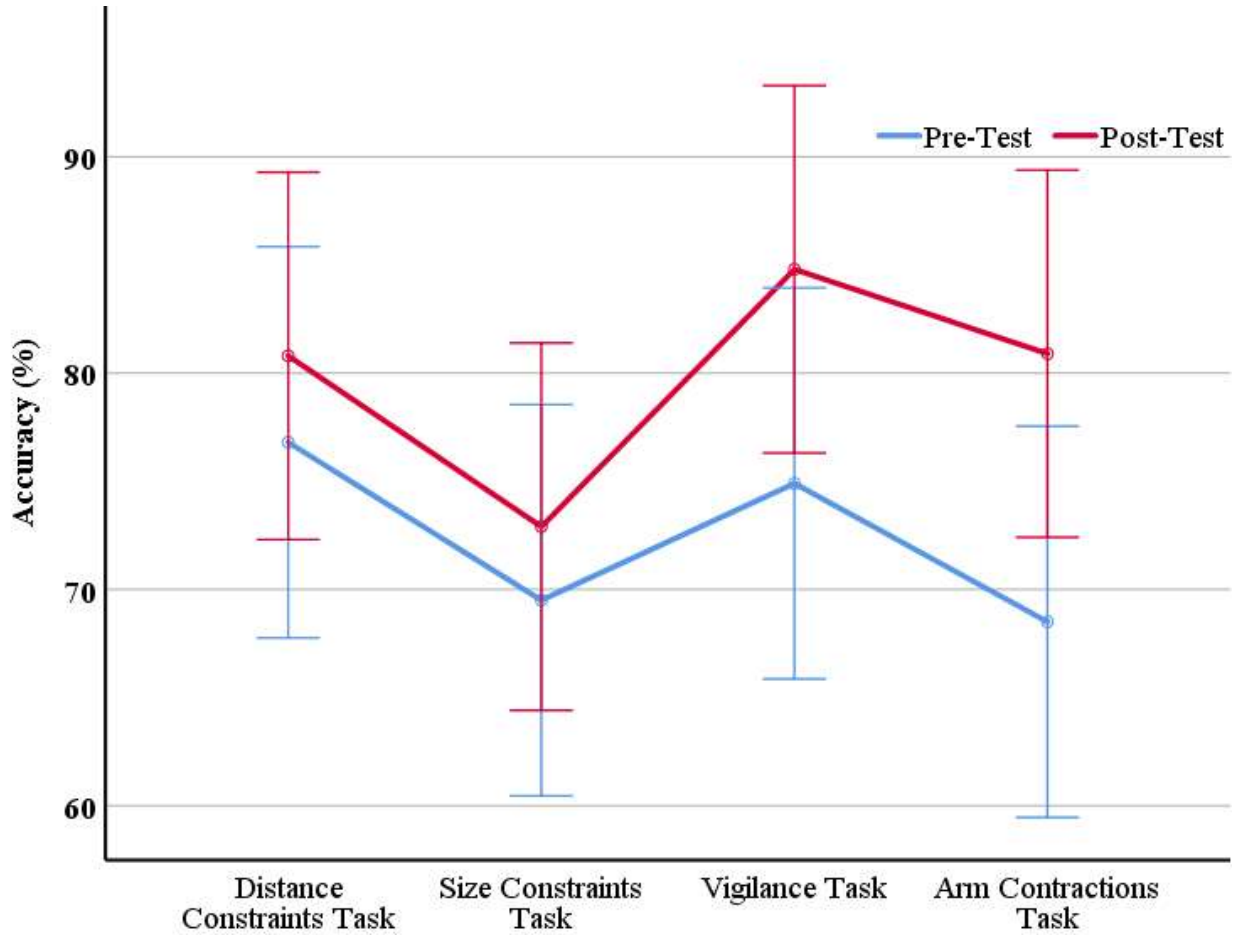


Figure 1: Pre- to Post-Test Differences in 3-Back Accuracy for Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

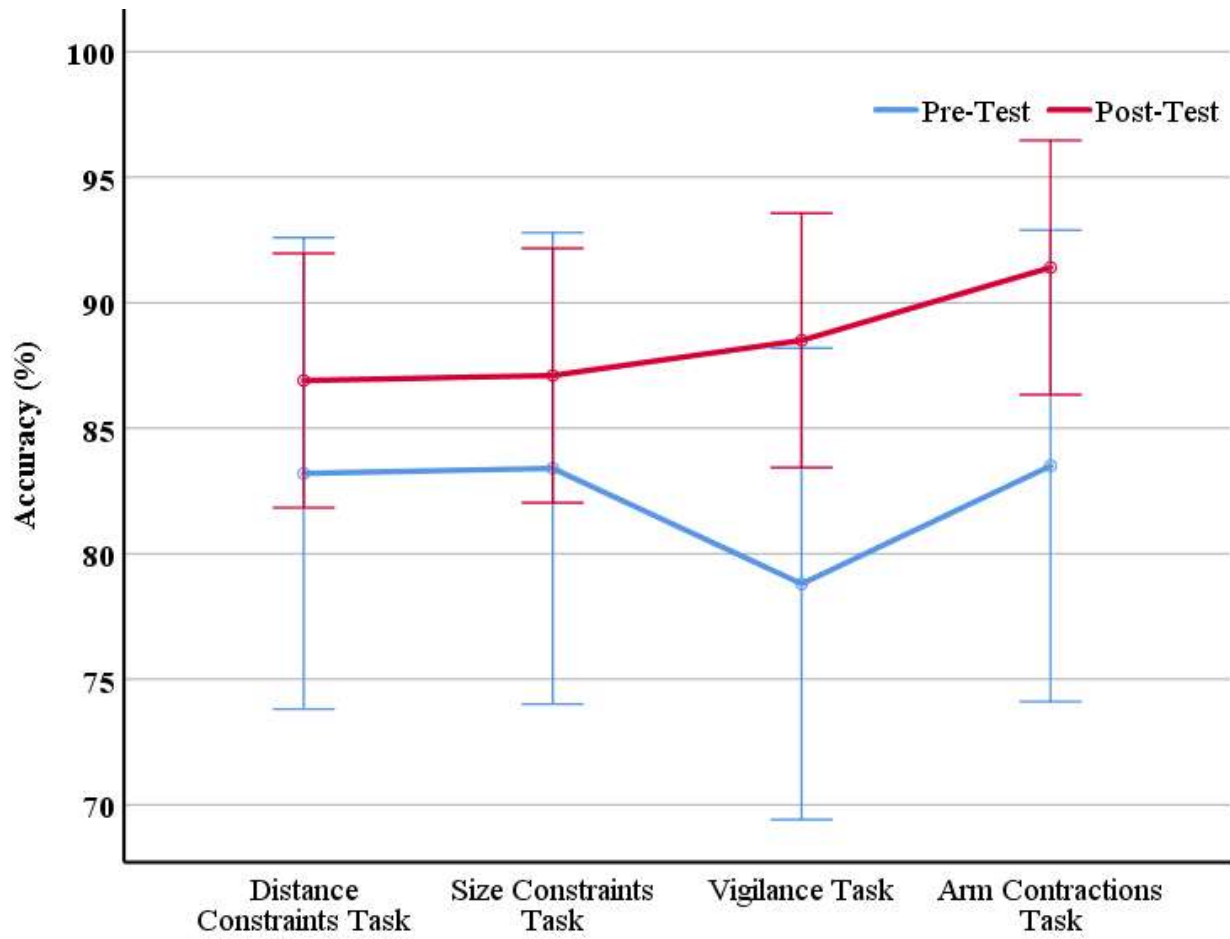


Figure 2: Pre- to Post-Test Differences in 3-Back Accuracy for Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

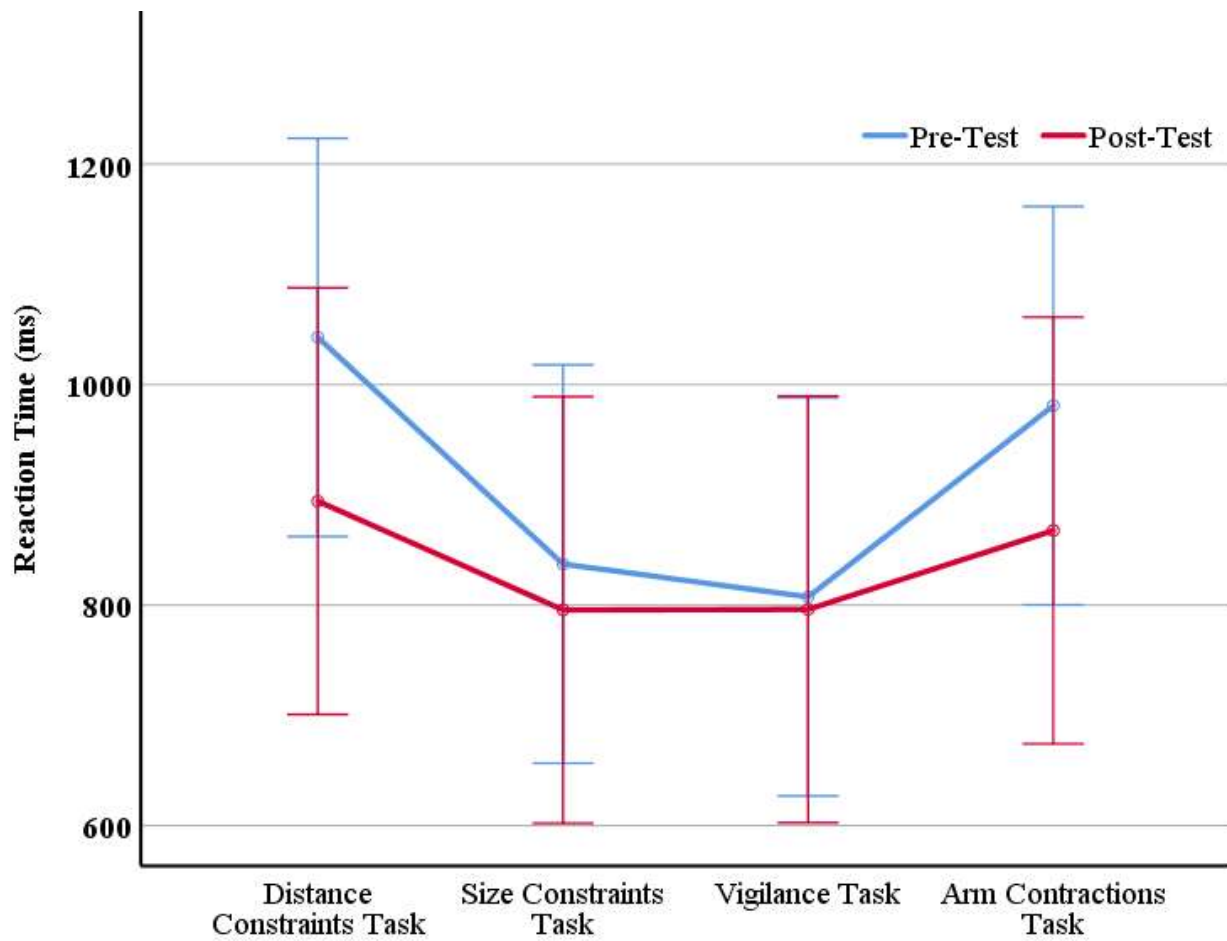


Figure 3: Pre- to Post-Test Differences in 3-Back Reaction Time for Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

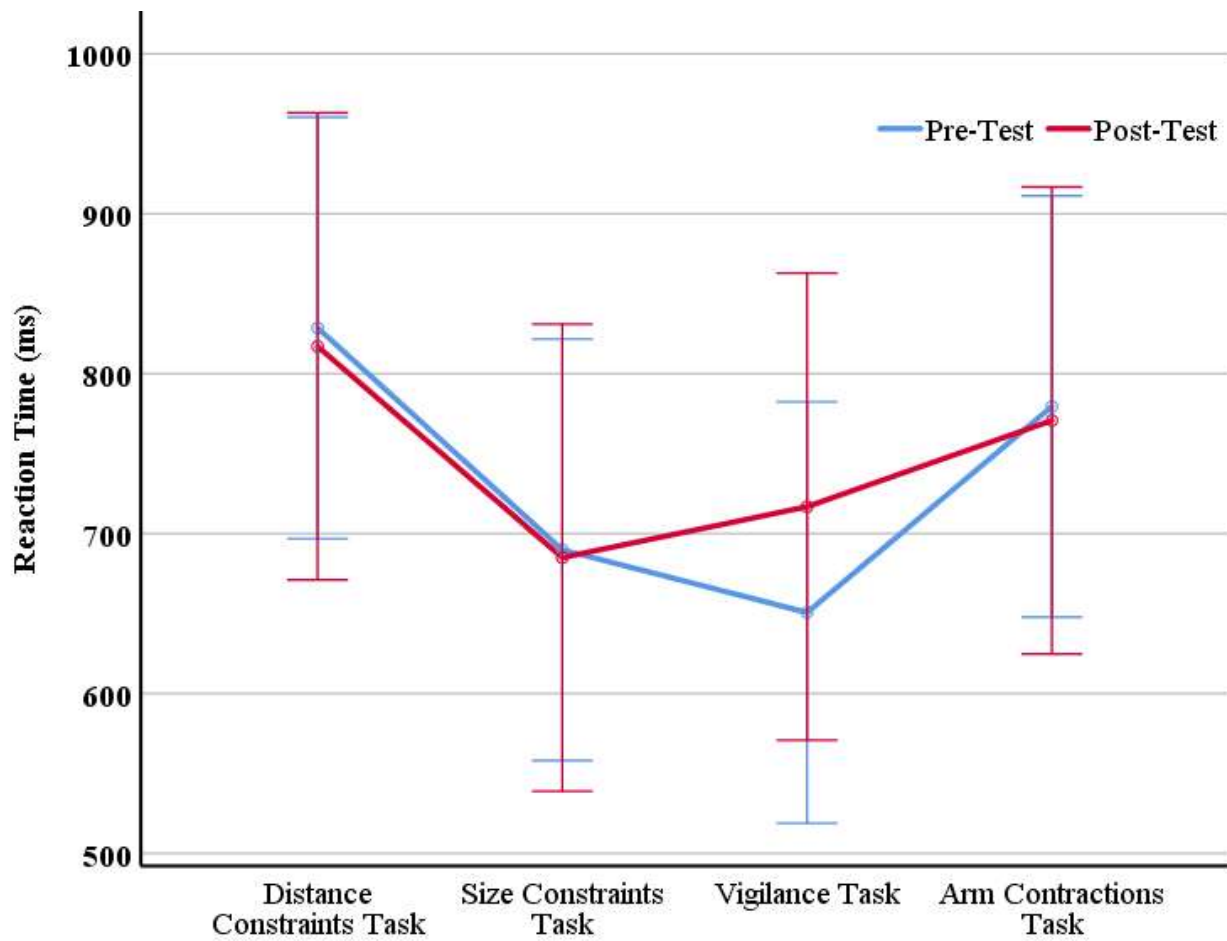


Figure 4: Pre- to Post-Test Differences in 3-Back Reaction Time for Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

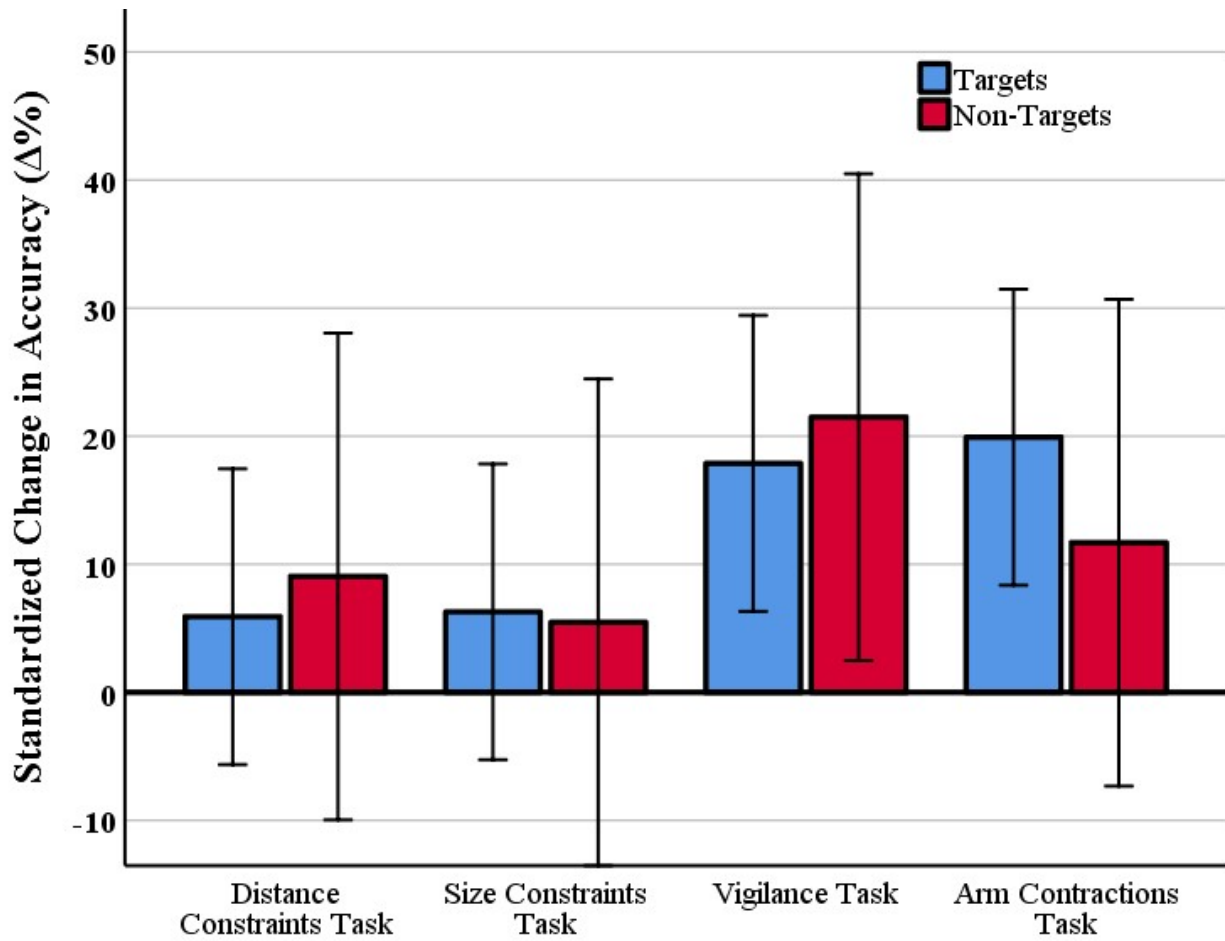


Figure 5: Pre- to Post-Test Standardized Changes in 3-Back Accuracy for Targets vs Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

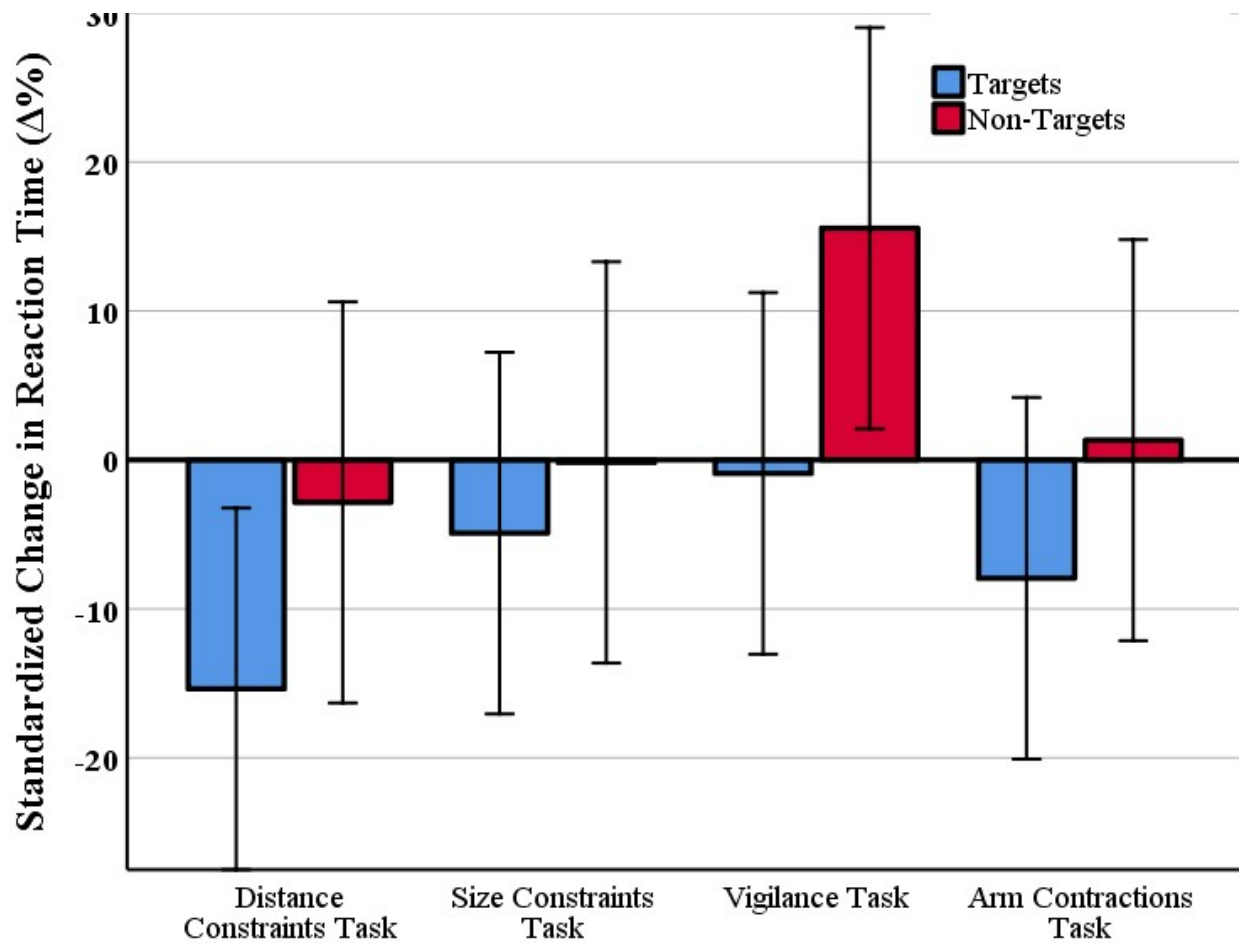


Figure 6: Pre- to Post-Test Standardized Changes in 3-Back Reaction Time for Targets vs Non-Targets after a Fatiguing Task. Error bars indicate $\pm 2 SE$.

Thresholded SPMF Image: p-value = 0.05 for Hboxy

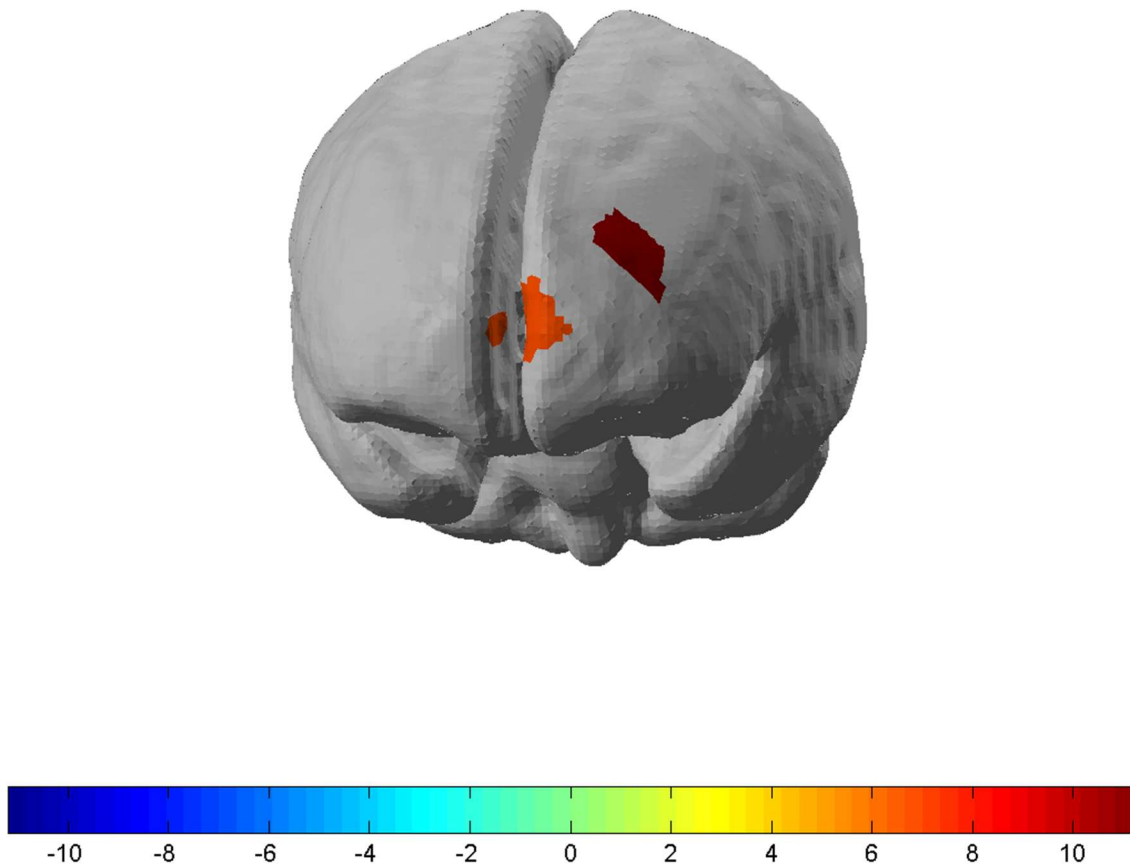


Figure 7: F-Map for Pre- to Post-Test Increases in 3-Back HbO₂ Levels After All Fatiguing Tasks at Channel 5 (dlPFC) and Channel 12 (dmPFC). $N = 11$.

Thresholded SPMF Image: p-value = 0.05 for Hboxy

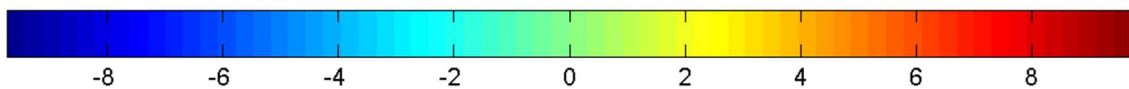
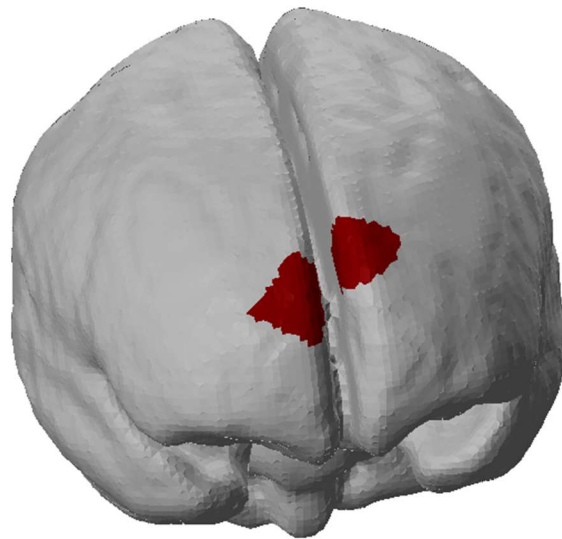


Figure 8: F-Map for Pre- to Post-Test Increases in 3-Back HbO₂ Levels for Size Constraints Task versus Distance Constraints Task at Channel 9 (dmPFC) and Channel 14 (dmPFC). $N = 6$.

Appendix D – Consent Form.

Permission to Take Part in a Human Research Study

Page 1 of 3



UNIVERSITY OF
CENTRAL FLORIDA

Title of research study: The effects of fatigue on cognition and motor performance

Investigator: Daniel McConnell, Ph.D.

Key Information: The following is a short summary of this study to help you decide whether or not to be a part of this study. More detailed information is listed later on in this form.

Why am I being invited to take part in a research study?

Researchers at the University of Central Florida (UCF) study many topics. To do this we need the help of people who agree to take part in a research study. You are being invited to take part in a research study which will include about 140 people at UCF. You have been asked to take part in this research study because you are a college-age individual. You must be between 18 and 25 years of age, have normal or corrected to normal vision, no other sensory or motor impairments, and be right-handed to be included in the research study.

Why is this research being done?

The purpose of the study is to further investigate the effects of fatigue on both cognitive and motor abilities, and to understand the role of brain activity in fatigue. Brain recording will use a new neuroimaging technique called Functional Near-Infrared Spectroscopy (fNIRS). This new technique is intended to be more comfortable for participants while simultaneously allowing researchers to investigate questions regarding movement and brain activation.

How long will the research last and what will I need to do?

The session will last about 2 hours. You will perform either a memory or motor task, then experience a fatiguing condition, and repeat the memory or motor task.

More detailed information about the study procedures can be found under *“What happens if I say yes, I want to be in this research?”*

Is there any way being in this study could be bad for me?

You may feel fatigue or muscle soreness following this study, but there are no other reasonably foreseeable risks or discomforts involved in taking part in this study. However, if you have had seizures in the past and/or have experienced nausea from using a computer or holding weights, we urge you to reconsider participation in this study.

Will being in this study help me in any way?

There are no benefits to you from your taking part in this research. We cannot promise any benefits to others from your taking part in this research.

Permission to Take Part in a Human Research Study

Page 2 of 3

What happens if I do not want to be in this research?

Your participation in this study is voluntary. You are free to withdraw your consent and discontinue participation in this study at any time without prejudice or penalty. Your decision to participate or not participate in this study will in no way affect your continued enrollment, grades, employment or your relationship with UCF or the individuals who may have an interest in this study.

Your alternative to participating in this research study is to not participate.

Detailed Information: The following is more detailed information about this study in addition to the information listed above.

What should I know about a research study?

- Someone will explain this research study to you.
- Whether or not you take part is up to you.
- You can choose not to take part.
- You can agree to take part and later change your mind.
- Your decision will not be held against you.
- You can ask all the questions you want before you decide.

Who can I talk to?

If you have questions, concerns, or complaints, or think the research has hurt you, talk to Dr. Daniel McConnell, Department of Psychology (407-823-1807; daniel.mcconnell@ucf.edu).

This research has been reviewed and approved by an Institutional Review Board ("IRB"). You may talk to them at 407-823-2901 or irb@ucf.edu if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

How many people will be studied?

We expect 140 people will be in this research study.

What happens if I say yes, I want to be in this research?

This study will take place in rooms 305 and 303K in the Psychology Building. A researcher will be waiting for you at room 305, after which you will be escorted to room 303K where the experiment will be conducted. You will be instructed to first complete a short demographics questionnaire.

Afterwards you will be fitted with the fNIRS cap (15 minutes) and complete a memory task (remembering letters presented on screen) or a motor task (using a stylus and tablet to point at targets on a computer screen), which will take 15 minutes. Following the initial task, you will participate in a fatiguing task that involves either looking at letters on a screen (vigilance task), repetitive pointing with a stylus (short distance task or long distance task), or holding a weight with your right arm for 90 seconds and then resting for 30 seconds (arm contractions task), which will take 45 minutes.

Afterwards, you will repeat either the memory task or motor task, which will again take 15 minutes.

We will then take off the fNIRS cap and give you post-participation information (5 minutes), after which you are free to leave. In total, the study will take at most 2 hours to complete.

Permission to Take Part in a Human Research Study

Page 3 of 3

We will measure changes in brain activity in the Prefrontal and Motor Cortex using an fNIRS imaging system. The fNIRS system uses a small, lightweight, and safe LED-based sensor worn on the forehead, and imaging is based on oxygenation-level dependent changes in tissue reflectivity. The sensor has two connecting straps that buckle at the back of the head. It is possible that additional support will be needed in order to secure the device. The resulting fit will feel snug against the forehead. This is done through the use of a thin gauze wrap over the sensors and around your head to add stability.

In addition to measuring brain activity, task performance is recorded by the computer.

What happens if I say yes, but I change my mind later?

You can leave the research at any time and it will not be held against you.

What happens to the information collected for the research?

Efforts will be made to limit the use and disclosure of your personal information, including research study to people who have a need to review this information. We cannot promise complete secrecy. Organizations that may inspect and copy your information include the IRB and other representatives of this organization.

Your participation in this study will be kept confidential, and your identity will not be stored with your data. Your responses will be linked to a code number that is not linked to your name or any other identifying information. All data will be stored in a locked room. Results of this study may be presented at conferences and/or published in books, journals, and/or the popular media.

What else do I need to know?

If you agree to take part in this research study, we will be giving you up to 2.0 SONA credits or a \$15 Amazon gift card for completing the study. Participants who leave early will still be compensated using the following rules for each compensation method. If you elect to receive SONA credits, you will be rewarded 0.5 credits per 30 minutes of participation. If you elect to receive gift card payment, you will be rewarded either a \$5 gift card (for up to 45 minutes of participation) or a \$10 gift card (for up to 90 minutes of participation).

Appendix E – Demographic Questionnaire.

Demographic Questionnaire

Are you right handed? YES/NO

Do you have normal vision? YES/NO

If no, do you wear corrective lenses? YES/NO

Are you wearing your corrective lenses at this time? YES/NO

Do you have any other sensory problems? YES/NO

Do you have any physical/motor problems that may affect your ability to perform a repetitive task with your right arm? YES/NO

Select your sex/gender that best describes you

Male

Female

Other

Prefer not to Answer

Enter your age: _____

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