

AN ANALYSIS OF EEG SPECTRAL POWER BETWEEN LABORATORY AND
NATURAL ENVIRONMENTS

by

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I would like to thank my committee members for helping me through this process. I would not have been about to complete this workout without you all!

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LIST OF ABBREVIATIONS

Abbreviation	Description
EEG	Electroencephalogram
PASAT	Paced Auditory Serial Addition Task
k Ω	Kiloohm
FFT	Fast Fourier Transform

ABSTRACT

Traditional electroencephalography (EEG) studies have been limited by logistical and practical issues that confine data collection to a structured laboratory setup. In this study we evaluated how externally valid EEG recordings in lab environments are. New mobile EEG systems provide flexibility in EEG recording procedures that allow researchers to venture out of the lab and collect data in more diverse environments. The present study used an open source commercially-available bioelectric amplifier system by OpenBCI to record EEG data through a mobile setup. Resting state EEG data were recorded from a sample of college students in a lab and an outdoor natural environment on Texas State University's campus. Additionally, EEG data were recorded while participants performed a working memory task, the paced auditory serial addition task (PASAT), in a lab and an outdoor natural environment. EEG spectral power was computed for the frontal midline site Fz, as well as the posterior site Oz via Fast Fourier Transform (FFT) for all conditions. Analysis focused on alpha, theta, and low beta ranges as per previous literature regarding EEG band power analysis during resting state, working memory and executive functioning tasks. Paired-sample *t*-tests and repeated measures ANOVAs did not show significant differences between the two environments concerning amplitude changes for the three bands of interest. Furthermore, scores on the PASAT also did not differ between environments. These results suggest that brain activity may not be significantly influenced by environmental changes.

I. INTRODUCTION

Psychological and neuroscientific researchers have long sought reliable and valid measurements of brain activity in order to better understand human behavior.

Technologies such as electroencephalography (EEG) provide a viable non-invasive method for detecting cortical activation in real time. EEG detects potential changes at the scalp due to the electrical activity of neurons firing in the cortex of the brain. Although EEG has been useful for the field of psychological neuroscience, one shortcoming has been its main use in strictly synthetic laboratory environments that lack the rich and diverse stimuli of the real world. The primary factor that confines traditional EEG research to laboratory environments is the physical limitations of the equipment.

Traditional EEG systems require large amplifiers, computers and electrically shielded booths that cannot be easily transported. Mobile EEG systems allow us to take participants out of the lab and into a wider variety of environments. These new mobile systems have more compact equipment, which can be easily transported and assembled in environments beyond the lab. The present study used spectral power analysis applied to EEG signals recorded from a mobile system to appraise the effect of environment on attention, executive function and working memory.

Mobile EEG Review

Traditional EEG recording systems are restrictive and sedentary by their nature. Data is usually recorded by specifically placed electrodes on the scalp, which sends signals to an amplifier. The brain-related voltage changes at the scalp are so weak that the signal needs to be multiplied by the amplifier before it can be processed. Additionally, the data from the electrodes is composed of analog sine waves that must be converted to a

digital format for data analysis. The sine waves are converted to a binary code of 1s and 0s. This conversion requires an analog to digital converter. The bulk of amplifiers and converters not only means that participants must have a direct wired connection to them, but also that the portability of these systems is extremely limited.

Recently, innovations in biofeedback technologies have opened the possibility of less restrictive recording of EEG data. In the case of this study, we elected to use an Open BCI mobile EEG system (OpenBCI, New York, NY, USA: see Method section below for details). This system still uses traditional wet electrodes that use electrically conductive gel to record cortical activity. However, the system involves a wearable unit that can locally record data to a Secure Digital (SD) card. This means that EEG data can be recorded wirelessly for each participant with minimal equipment. With the use of this system, EEG recording equipment can be moved and set up within a reasonable window of time, and manipulations of environment can be introduced. This study used mobile EEG to assess cognition-related brain activity during a single cognitive task while being one of the first to introduce an environmental manipulation.

The search for a mobile EEG solution that is cost effective and produces minimal artifacts has made significant progress in recent years. However, the use of mobile EEG has been mostly used as proof of concept equipment testing and has used narrowly focused cognitive measures. In an analysis of 22 papers concerning mobile EEG, 82% focused on attention while the other 18% focused on various other singular cognitive measures such as meditation, motivation, and emotion (Xu et al., 2018). Mobile EEG is proven to be a reliable method to obtain measures of brain activity, but like traditional EEG it has been primarily used in laboratory environments. However, few studies have

yet exploited the portability of mobile EEG to evaluate the relationship between cognition and environment by measuring the brain activity of participants in a real environment outside of a laboratory setting. One exception to this is the use of virtual reality (VR) to understand complex cortical interactions during naturalistic tasks and environments. Tromp et al. (2018) assessed the validity of VR and EEG for language processing in a natural environment via measurement of the N400 event-related potential (ERP). The N400 is a stimulus-locked brain response that reflects a mismatch between auditory or visual stimuli; in this experiment, it was used as a marker of semantic mismatch among linguistic stimuli. Tromp et al. (2018) found a greater N400 for the mismatch versus match semantic conditions (Tromp et al., 2018). These findings are consistent with what we would expect from participants in a laboratory environment outside of a virtual environment. Furthermore, Maclin et al. (2011) gives an in-depth review of cortical activation and resource allocation for multitasking during video game practice. Virtual environments that reflect the same conditions in the real world have been shown to provide similar cortical activity to what we would see in a real environment. However, few studies have taken participants physically out of the lab, which is what we proposed to do in this study.

From a brief review of the literature, one can see that the analysis of EEG data and mobile EEG during cognitive assessment are well-tested and effective tools (Sauseng et al., 2009, Schutte et al., 2017, Dai et al., 2017). The use of VR and video games in general lays the framework for cortical activation we should expect to see during complex tasks in a complex environment. However, one issue past studies have not yet satisfactorily addressed is the influence of task environment on these EEG measures. Is

laboratory EEG data externally valid? If there are observable differences in even resting state EEGs within subjects in natural versus laboratory environments, then we must question the validity of running subjects in exclusively synthetic laboratory environments. Laboratory environments lack the additional stimuli such as people, movement of objects and environmental noises that exist in natural environments, and therefore it is important to consider elements of cognitive processing that are not able to be observed in the lab. The differences in environmental stimuli that exist when comparing a laboratory versus natural setting may be significant enough to require a change of attentional resource implementation. It is worth considering the possibility that this change in environmental stimuli could influence task performance as well as the level of theta and beta EEG activity. We also chose to analysis alpha during all conditions in an exploratory manor as an index of alertness and vigilant attention. The present study used a mobile EEG to take subjects to both laboratory and natural environments to assess this question.

Ongoing Resting EEG

Ongoing EEG analysis can measure neural oscillations within certain frequency bands to assess cortical activation related to different mental states and cognitive functions (Başar et al., 1992; Pantev et al., 1994). A standard method for analyzing EEG data is by measuring the power, or proportion, of oscillatory patterns from each electrode and breaking them down into bands of frequencies that are associated with specific cognitive properties. For this study, there are three frequency bands of interest: theta, alpha and low beta. Theta waves range from 4-7 Hz and are commonly studied in relation to memory processing (Klimesch, 1996). Alpha waves, ranging from 8-12 Hz, are

associated with cognitive inhibition and are present in relaxed individuals (Klimesch et al., 2007). Additionally, many studies evaluated a contrast in alpha during eyes open and eyes closed resting state conditions such that alpha increases, most notably in posterior sites, during eyes closed conditions (Legewie et al., 1969; Adrian & Matthews, 1934); the increase in alpha during eyes closed conditions is believed to reflect an “idling” state of the cortex driven by the thalamus. This observable difference has the potential to be used as an index of how environmental manipulation may influence internal cognitive processes in the sense that environmental stimuli might disrupt the brain’s idling state. Lastly, beta waves, ranging from 16-31 Hz, are associated with alertness and an individual’s engagement to a task (Neuper and Pfurtscheller, 2001).

However, there is a lack of research investigating brain activity under different environments outside the lab. The study reported here used ongoing EEG to measure cortical activation during a manipulation of task environment and not just task condition. Specifically, ongoing EEG data was measured during two separate tasks to detect what, if any, cortical differences there were between different task environments, lab versus an outdoor natural environment. The laboratory environment was a typical cognitive psychology lab on the Texas State University campus that is comparable to traditional EEG laboratories. The natural environment in this study was an outdoor section of the Texas State University campus located just outside of the laboratory environment. The first task was a resting state task in which ongoing EEG data was recorded during participant eyes open and eyes closed resting states. Resting state EEG data reflects general levels of alertness and attentional vigilance and can also be linked to default mode brain network activity (Scheeringa et al., 2008). Thus, any differences in alertness

and vigilance across recording environments during the resting task should manifest as differences in EEG power across the three frequency ranges of interest (theta, alpha, low beta).

EEG Oscillations, Working Memory, and Executive Function

This methodology was also applied to EEG data during a task that engaged cognitive processing. The task was an auditory math task, the paced auditory serial addition test (PASAT), which employs participants to engage executive functioning processes in the context of working memory. Executive function refers to the controlled implementation of cognitive processing and behavior (Barkley, 2012). Working memory is defined as the temporary mental storage of sensory and cognitive information (typically 5 to 9 seconds; Miller, 1956), a mental ability that both requires and can be used as an index of executive functioning (Diamond, 2013).

In general, executive function and working memory processes are associated with increased activation in theta and beta band EEG activity (Dai et al., 2017; Sauseng et al., 2009; Schutte et al., 2017; Onton et al., 2005). For example, Dai et al. (2017) illustrated the relationship between working memory tasks and theta band activity with a visual n -back task. For their experiment, subjects performed visual n -back tests with two conditions: 0-back and 2-back. The n -back test is a performance task in which the subject is presented a sequence of stimuli and must answer if the current stimulus matches the stimuli from n steps previous in the sequence. The 0-back provides a control condition for the 2-back condition, which engages working memory. For the 2-back task, higher levels of theta activity were observed in frontal, temporal and occipital lobes.

Amplitude changes in the theta range are most commonly found at frontal midline sites during focused attention and when short-term memory is active (Aftanas & Golosheikine, 2001; Burgess & Gruzelier, 1997). Additionally, amplitude power of theta is positively related to increases in task difficulty at frontal sites (Kahana et al., 1999) possibly suggesting that spikes in theta oscillations are related to the coordination of mental resources to execute a task. Furthermore, log spectral independent component analysis applied to time frequency transformations has shown an increase in frontal midline low beta (12 – 15 Hz) during task related trials in a working memory task (Onton et al., 2005). This shows that working memory can be indexed by power increases in theta and low beta at frontal midline sites.

We can see from previous literature that EEG frequency band power analysis for executive functioning processes such as working memory tasks yields robust theta and low beta band activity modulations (Dai et al., 2017; Sauseng et al., 2009; Schutte et al., 2017). The present study employed a task that engaged executively controlled working memory processes to evaluate spectral power changes at frontal midline sites across environment types. If environment influences brain activity, then theta-band and low beta-band EEG power analysis should differ between laboratory and naturalistic environments. To predict the nature of this hypothesized EEG power difference, it is pertinent to understand the possible ways in which different environmental settings might affect working memory, executive functioning and attention.

Attentional Resource Theory

A key component of this study is the introduction of distracting erratic stimuli in a natural environment that may act to disrupt or have some effect on cognitive processes.

The cognitive effects of such distracting stimuli can be described by Kahnemen's Attentional Resource Theory of attention (Kahnemen, 1973). Kahnemen's model states that an individual has a limited amount of mental resources they can allocate to perform a task. Kahneman proposed that some tasks may be more or less difficult than others, and the mental effort necessary to allocate those resources for each task may vary. Another component of this model of attention is that the capacity of these processes may be increased or decreased by intangible factors specific to the individual (i.e. mood or motivation). Lastly, Kahnemen states that several tasks can be performed at once so long as the total mental resources necessary to perform each task does not exceed the total limit of the individual's capacity. According to this model of attention, the additional and erratic visual and auditory stimuli in the natural environment should draw attentional resources and limit the capacity left to be delegated to the performance of the cognitive task. This model suggests that task behavior and associated brain states that reflect attentional and alerting processes should be affected by the natural environment due to the increased frequency of erratic stimuli.

Relating Kahnemen's theory of attention to EEG spectral power, the three frequency bands of interest in this study can be used to index how attentional resources are implemented during different task conditions. The theoretical framework of this study is that environments with differing degrees of distracting elements will require attentional processes to be altered. For example, we propose that in an environment with minimal distractions attentional resources can be fully applied to perform a task, and thus participant responses are maximally efficient. In contrast, an outdoor natural

environment, which has many distracting elements, may cause the brain to implement attentional resources in an altered strategy than in a controlled environment.

There are two possible ways to apply Kahnemen's attentional resource theory to more accurately predict the relationship between environment and attention related changes in EEG spectral power. The first is that in a naturalistic outdoor environment there is a diversion of attentional resources. In the natural environment, the participant is now being asked to pay attention to both the distracting auditory and visual elements around them as well as working memory task given by the researcher. Which effectively means each participant has two tasks to attend to and more brain regions are required to process and integrate that information. This theory can be evaluated by measuring the power of the three frequency bands of interest (theta, alpha and beta) as an index of attentional mental resource application. In the natural environment, potentially less mental resources can be applied to the working memory task leading to a corresponding reduction in theta and beta band activity and an increase in alpha band activity. However, there is not much empirical support for this theory. Recent literature regarding divided attention during multitasking showed no significant activation of additional brain regions (Nijboer et al., 2014; Moisala et al., 2015). Additionally, analysis of EEG data during a distracted driving task showed an increase in theta band oscillations and a decrease in alpha band oscillations in frontal and occipital sites (Wang et al., 2018).

The alternative application of Kahnemen's theory is a focusing of attentional resources in the natural environment. Distributed attention to multiple spatial locations has been shown to produce 4 Hz modulation of theta band activity (Landau et al., 2015). Additionally, observations of alpha activity may be a useful method for evaluating

attentional resources. Alpha desynchronization has been observed to be associated with attentional processes (Ray & Cole, 1985). More recent literature suggests irrelevant sounds attract attention to its location and trigger a bilateral desynchronization of alpha activity at occipital sites (Störmer et al., 2016). These studies suggest that distracting auditory and visual stimuli are present, alpha suppressing may be an index of a reduction in attentional processes to a relevant task that is independent to the surrounding environment. Therefore, in the natural environment where more distracting elements are present more attentional resources may be necessary to overcome the external distractions and complete the task. This focusing of attentional resources may manifest as an increase in theta band activity and a decrease in alpha band activity, which may be an index of an increase in attention.

Hypothesis and Prediction

The primary hypothesis for the proposed study is that if the additional stimuli that are present in naturalistic environments distract the attention of participant, then this will lead to a change in EEG power and a decrease in performance of the behavioral tasks. In other words, if we see mean differences for the target frequency bands, theta, alpha and beta, between the lab and natural environments, then we can make an inference concerning the external validity of recording EEG data from primarily laboratory environments. It is known from the literature that in a simple cognitive task the employs executive functioning processes like working memory the EEG data should show significant theta/beta activation activity (Dai et al., 2017, Sauseng et al., 2009, Schutte et al., 2017). The prediction is that the EEG spectral power analysis will change in the natural environment because of the increased visual and auditory distracting stimuli that

will present. However, the predicted direction of the change in theta/ beta EEG activity is unclear. If the erratic and distracting stimuli cause subjects to have to focus harder on the task than they would in a laboratory setting, then theta and beta EEG activity should increase in the natural environment relative to the lab environment. In contrast, is the distracting stimuli in the natural environment cause attentional resources to be diverted, leaving less resources to be allocated to completing the task; this in turn would cause a corresponding decrease in theta and beta EEG activity.

The primary hypothesis for this study is that the introduction of erratic and attention-provoking auditory and visual stimuli in the natural environment will detract from performance on a working memory and executive function task as well as arousal and attention processes that are engaged during the resting conditions. Our view is that participants will have to focus with more mental effort on the task in the natural environment. Therefore, frontal sites that would be indicative of working memory performance will show increases in theta and low beta frequencies as well as a decrease in alpha activity (H_1). Additionally, this alteration in cortical activity will be reflected in participant performance. Concerning the scores of the PASAT, the prediction is that participants will perform worse on this task in the naturalistic condition because participants will be subject distracting stimuli that will draw attentional resources away leaving less resources available to perform the task (H_2). Concerning the resting conditions, we predict that in the natural environment there will be an increase in attention to the additional external stimuli during both eyes open and eyes closed resting conditions. This increase in attention will also yield an increase in theta and low beta at frontal midline sites as well as a decrease in alpha levels (H_3).

II. METHODS

Participants

All procedures were approved by the Institutional Review Board at Texas State University. For this study, 26 young adults were recruited through Texas State University's SONA System recruiting pool. However, data from five participants were lost due to equipment malfunction leading to an overall N of 21 ($M = 19.27$, $SD = 2.01$), 9 male and 17 females. The participants were given course credit for participation in the study.

Design

The study was a within-subjects experimental design with the environment factor (lab and natural environment) counterbalanced across participants. The conditions and tasks (cognitive, resting) were counterbalanced across all participants. In the resting state task, participants underwent 10 minutes of EEG recording while sitting quietly in a comfortable padded chair in a darkened room (5 minutes eyes open and 5 minutes eyes closed interleaved in 1-minute intervals; eyes open/closed order was balanced across participants). Participants were instructed to remain relaxed, yet alert and awake at all times during recording.

The cognitive task was a serial addition task called the paced auditory serial addition test (PASAT). The PASAT is a cognitive test that is used to measure auditory information processing (Gronwall, 1974). We chose this task specifically because it has been shown to require working memory (Forn, 2006) and executive functioning processes (Rogers, 2007). When participants perform the task, they should be engaging in

these cognitive functions, such as working memory, and that should be reflected in the EEG signal being recorded. In the PASAT task, participants hear a single digit once every 3 seconds and must add the most recent pair of digits together. For example, the first two digits may be “4” and “8” so the participant should write “12”. If the next digit is “2” the participant should score “10”, as that is the new sum of 8 and 2. Participants are scored out of 60 possible answers and were given two prespecified versions of the test to ensure standardization of the presentation. Participants were asked to hand write their answers on a premade score sheet. The two versions of the test were administered and counterbalanced to each participant, ensuring they were given a new version of the test in each environment. Each participant was given a brief practice run before they began the task and asked again in the second environment if they needed to reconfirm the rules.

For the resting task, the independent variables were environment (lab and natural environment) and resting state (eyes closed, eyes open). The dependent variable was the computed values of EEG spectral power for each participant. For the PASAT, the independent variable was environment, whereas the dependent variables were PASAT scores and the computed values of EEG spectral power for each participant. These design parameters yielded six blocks of data for each participant. EEG data was collected for each participant during both environmental conditions and all task blocks. The conditions and tasks (cognitive, resting) were counterbalanced across all participants.

Materials

Electroencephalographic brain activity was recorded using an OpenBCI Cyton mobile EEG system (OpenBCI, New York, NY, USA). EEG recording parameters followed standard recommendations (Picton et al., 2017). EEG signals were measured

from electrodes placed on the scalp at 16 international 10-20-electrode locations (FP1, FP2, F1, FZ, F2, C3, C4, O1, P3, PZ, P4, O2, OZ, M1, M2, CZ). One additional electrode was affixed below the left eye to account for vertical and horizontal electrooculographic (EOG) activity (eye movements and blinks). All channels were amplified by an OpenBCI amplifier initially sampled at 125 Hz and upsampled to 250 Hz. All electrode impedances were kept below 5 k Ω . The cap was connected to an amplification unit that was wirelessly connected to a USB dongle plugged into a recording laptop. The amp/USB connection used a high-power Bluetooth signal to control the device. Each task condition (resting and working memory tasks) was recorded in different data blocks to a Secure Digital (SD) card inside the EEG amplification unit over 5-minute intervals with a 250 Hz sampling rate. The graphics user interface (GUI) used for data collection records data for preset periods of time. Due to a limitation of the Cyton unit that leads to a shorter time length of data being recorded than specified, EEG was recorded for approximately 10 minutes and the first 5-minutes of data reflecting task performance was retained for analysis. For the PASAT, participants listened to prerecorded audio files of the test through headphones. To ensure that participants would still be able to hear the distracting elements of the natural environment, Sennheiser HD-6XX open back headphones were used. The open back headphones offer no noise cancellation while still providing adequate sound of the task stimuli to the participants. Participants scored their answers on a printed test form by hand, but participants were unaware of their performance.

Procedures

Upon arrival, participants signed a consent form and be informed of the procedure for the experiment. Participants head diameter and nasion-inion measurements were taken to ensure proper cap placement. The subjects then put on the cap, and the EEG equipment was assembled for recording. The EEG cap was plugged into the EEG amplification unit that attaches to the back of the cap. Additionally, the SD card was inserted into the amplification unit for data to be written to it. Lastly, the USB chip that identifies the serial of the amplification unit was plugged into a laptop computer which is used to start, stop and monitor the EEG data. Depending on the order of the counterbalancing, participants began the experiment in either the Cognitive Electrophysiology lab on the Texas State Campus (ELA 222) or in an outdoor area just outside the lab on a bench outside of the Evans Liberal Arts Building (ELA). Participants then performed a 5-minute resting state eyes open task block, a 5-minute resting state eyes closed task block, and the PASAT. Equipment was then packed and moved with the participant to the other location and the process repeated over two environmental conditions and six task blocks in total.



Figure 1. Pictures of the laboratory environment (left) located in ELA 222 on Texas State University's campus and the natural environment (right) located in the Quad outside of the ELA building on Texas State University's campus.

Data Coding and Collection

The raw data from each block was locally written in hexadecimal to the SD card within the cyton unit, which was converted to an Excel spread sheet. Each of these converted data files was trimmed and processed within MATLAB computing software (MathWorks, Massachusetts). Across all tasks and conditions, each participant had a total of roughly 20 minutes of resting state continuous EEG data that was then decomposed into 1-second baseline-corrected epochs with 50% overlap. After data collection, EEG data was artifact-scored using standard techniques used by Trujillo et al. (2017). This includes removal of data portions contaminated by eye blinks/movements, muscle activity, head motion, and other signal artifacts. EEG spectral power density ($\mu V^2/Hz$) was computed via Fast Fourier Transform (FFT) analysis using a 1-second Hamming window and converted to decibel units. The average number of retained trials was 508 ± 26.21 in the lab and 492 ± 16.90 in the natural environment during eyes closed resting conditions. Paired samples *t*-test analysis showed no significant difference in the number of trials when comparing lab versus natural environments [$t(21) = .558, p = .583, d = .12$].

The average number of retained trials was 475 +/- 18.14 in the lab and 430 +/- 20.27 in the natural environment during eyes open resting conditions. Paired samples *t*-test analysis showed no significant difference in the number of trials when comparing lab versus natural environments [$t(20) = 1.954, p = .066, d = .43$]. The average number of retained trials was 408 +/- 22.33 in the lab and 358 +/- 22.46 in the natural environment during eyes closed resting conditions. Paired samples *t*-test analysis showed no significant difference in the number of trials when comparing lab versus natural environments [$t(20) = 1.694, p = .107, d = .37$].

Analytic Strategy

To test the two hypotheses for this study, we computed group descriptive statistics for both the naturalistic and laboratory conditions. Scores on the PASAT were computed as means for all the participants for each condition, which allows for the percentage of correct answers to be calculated and compared across environments. FFT-based spectral power was computed for each participant for each environmental condition. Spectral power was plotted to show the difference of the power averages for the laboratory and naturalistic environments for all conditions (PASAT and resting). Paired-samples *t*-tests were computed testing for between-condition differences (naturalistic versus laboratory) in the PASAT scores and EEG spectral power during the PASAT, with separate tests performed for theta, alpha, and beta range power. *T*-tests were corrected for multiple comparisons using the Holm-Bonferroni procedure (Holm, 1979). Additionally, 2x2 repeated measures ANOVAs were computed to test for main effects of environment and resting state, condition as well as to test for any possible interactions. ANOVAs were also corrected for multiple comparisons using the Holm-Bonferroni procedure (Holm, 1979).

For this study there were three frequency bands of interest: alpha, theta and low beta. Following previous research regarding working memory and executive function, alpha and theta frequencies were assessed at frontal (Fz) and posterior sites (Oz) (Sauseng et al., 2005). Additionally, assessment of low beta activity was done through analysis of midline frontal site Fz (Schutte et al., 2017).

III. RESULTS

PASAT Performance Behavioral Analysis

Paired samples *t*-tests were used to compare mean differences of performance in the lab versus natural conditions. Subjects were scored out of 60 total correct answers. No significant differences were found [$t(19) = .432, p = .67, d = .09$].

Table 1. Descriptive statistics during the PASAT conditions in the lab and natural environments.

	Mean	N	Std. Deviation
PASAT Lab	53.29	21	6.972
PASAT Natural	52.76	21	8.402

EEG Spectral Power Analysis: Resting State Task

The grand-average resting state EEG power spectrum at sites Fz and Oz are displayed in Figures 2 and 3, respectively. Mean resting state EEG spectral power for all electrodes, frequency bands, and experimental conditions can be found in Table 2.

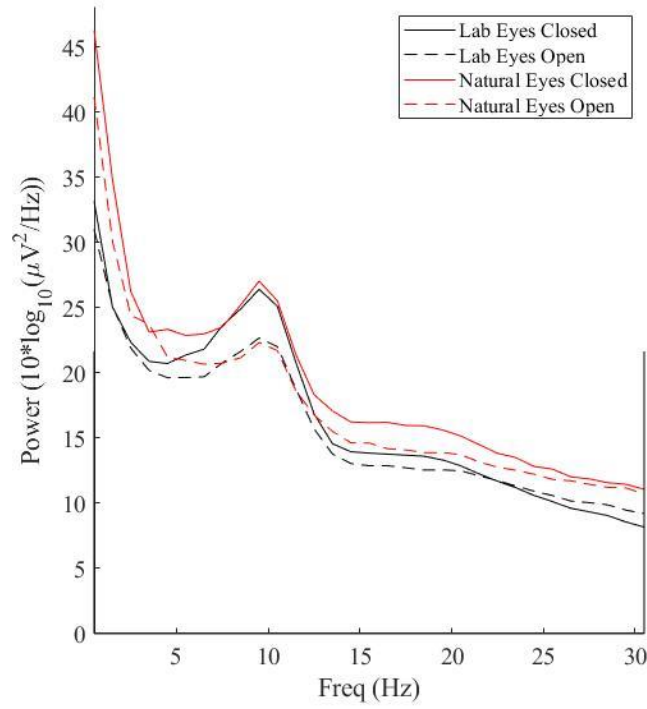


Figure 2. Resting state EEG power spectrum from representative frontal midline site Fz. Black lines = lab condition, red lines = natural condition. Solid lines = eyes closed, dashed lines = eyes open. All values in decibel units.

Spectral power means were qualitatively higher across theta, alpha and low beta frequency ranges during eyes closed versus eyes closed conditions at both frontal midline site Fz and posterior site Oz. However, there was no apparent effects of environment on resting state EEG power. These findings were confirmed via 2 x 2 repeated measures ANOVA. For the theta range power at site Fz, we found no significant main effect of environment [$F(1,19) = .992, p_{corrected} = 1, n_p^2 = .050$], a significant main effect for resting condition [$F(1,19) = 14.904, p_{corrected} = .006, n_p^2 = .440$], and no interaction [$F(1,19) = .085, p_{corrected} = 1, n_p^2 = .004$]. For theta power at site Oz, we found no

significant main effect of environment [$F(1,19) = 1.224, p_{corrected} = 1, n_p^2 = .061$], no significant main effect for resting condition [$F(1,19) = 3.792, p_{corrected} = .33, n_p^2 = .166$], and no interaction [$F(1,19) = 1.521, p_{corrected} = 1, n_p^2 = .074$].

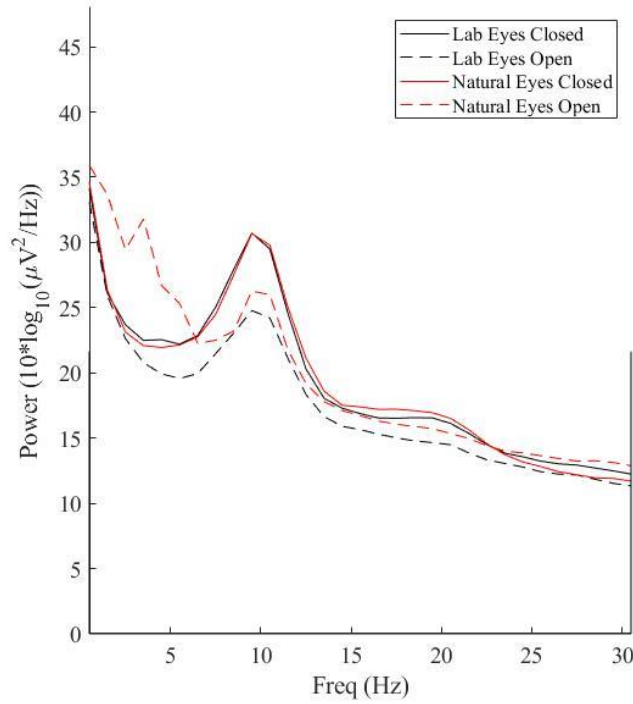


Figure 3. Resting state EEG power spectrum from representative posterior site Oz. Black lines = lab condition, red lines = natural condition. Solid lines = eyes closed, dashed lines = eyes open. All values in decibel units.

For the alpha range power at site Fz, we found no significant main effect of environment [$F(1,19) = .117, p_{corrected} = 1, n_p^2 = .006$], a significant main effect for resting condition [$F(1,19) = 35.962, p_{corrected} = .006, n_p^2 = .654$], and no interaction

$[F(1,19) = .598, p_{corrected} = 1, n_p^2 = .031]$. For alpha at site Oz, we found no significant main effect of environment $[F(1,19) = .201, p_{corrected} = 1, n_p^2 = .010]$, a significant main effect for resting condition $[F(1,19) = 23.273, p_{corrected} = .006, n_p^2 = .551]$, and no interaction $[F(1,19) = .003, p_{corrected} = 1, n_p^2 = .000]$.

Table 2. Averages of the EEG spectral power during resting state eyes open and resting state eyes closed in both laboratory and natural conditions at sites Fz and Oz for frequency bands theta, alpha and beta.

EEG band	Electrode site	Lab eyes closed	Natural eyes closed	Lab eyes open	Natural eyes open
Theta	Fz	20.31	20.93	19.22	19.99
	Oz	20.84	21.00	19.22	20.56
Alpha	Fz	20.81	21.36	18.80	18.62
	Oz	23.63	23.87	20.39	20.71
Beta	Fz	13.19	14.25	12.31	13.75
	Oz	16.28	16.80	14.91	15.47

For the low beta range power at site Fz, we found no significant main effect of environment $[F(1,19) = 1.872, p_{corrected} = 1, n_p^2 = .090]$, a significant main effect for resting condition $[F(1,19) = 23.840, p_{corrected} = .006, n_p^2 = .556]$, and no interaction $[F(1,19) = .151, p_{corrected} = 1, n_p^2 = .008]$. For low beta power at site Oz, we found no significant main effect of environment $[F(1,19) = 1.011, p_{corrected} = 1, n_p^2 = .051]$, a significant main effect for resting condition $[F(1,19) = 18.947, p_{corrected} = .006, n_p^2 = .499]$, and no significant interaction $[F(1,19) = .004, p_{corrected} = 1, n_p^2 = .000]$.

EEG Spectral Power Analysis: PASAT

The grand-averaged EEG power spectrum at sites Fz and Oz is displayed in Figures 4 and 5, respectively. Mean PASAT EEG spectral power for all electrodes, frequency bands, and experimental conditions can be found in Table 3.

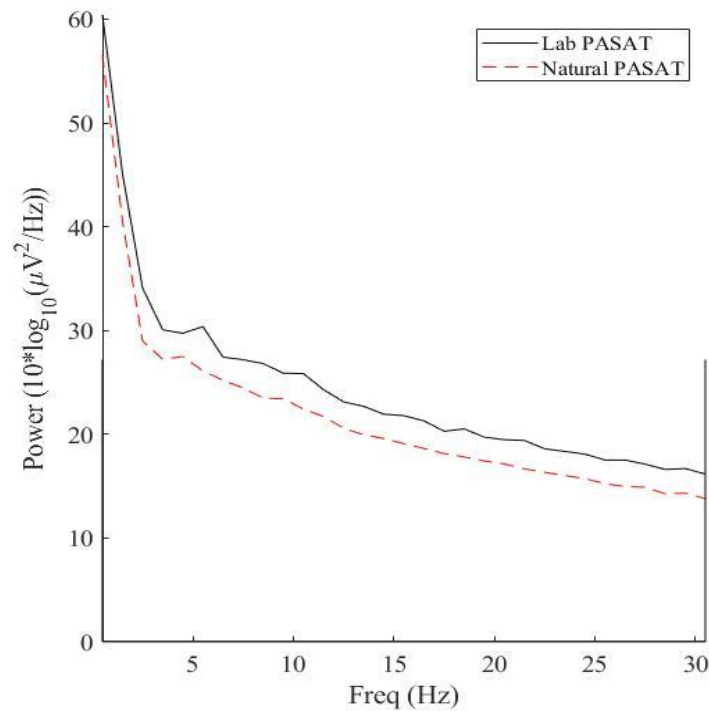


Figure 4. PASAT EEG power spectrum from representative frontal midline site Fz. Solid black line = lab condition, dashed red line = natural condition. All values in decibel units.

Qualitatively, higher EEG spectral power was observed in the laboratory versus natural environment during the math tasks at site Fz, whereas no such qualitative difference was observed at site Oz. However, statistical testing indicated that the potential

Fz difference was not significant for any frequency band. For theta power, there was no significant difference between environment conditions at site Fz [$t(19) = .259$, $p_{corrected} = 1$ $d = .06$], or at site Oz [$t(19) = 1.577$, $p_{corrected} = .786$ $d = .35$]. There was also no significant difference in low beta power during the math task at site Fz [$t(19) = .032$, $p_{corrected} = 1$ $d = .01$], or at site Oz [$t(19) = -.531$, $p_{corrected} = 1$ $d = -0.12$]. Lastly, there was no significant difference in alpha power during the math task at site Fz [$t(19) = .403$, $p_{corrected} = 1$ $d = .09$], or at site Oz [$t(19) = .998$, $p_{corrected} = 1$ $d = .22$].

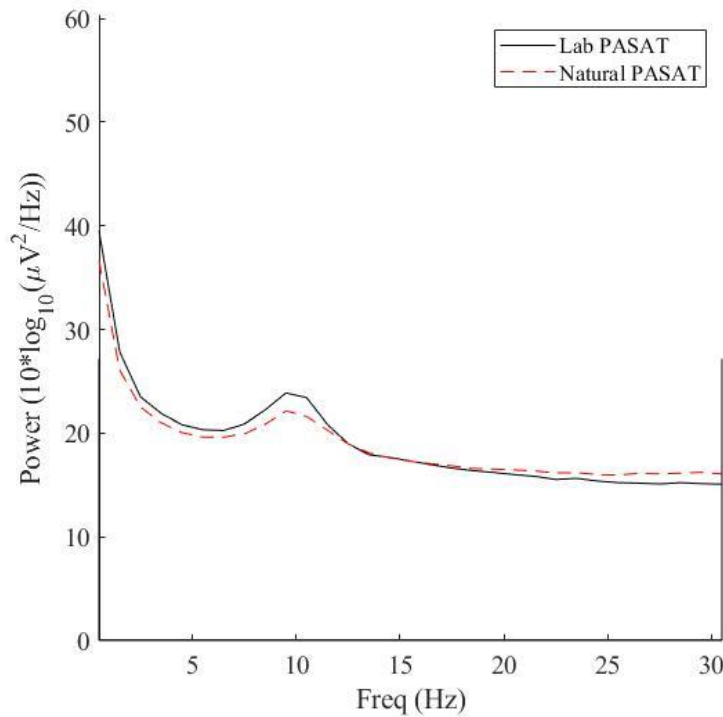


Figure 5. PASAT EEG power spectrum from representative posterior site Oz. Solid black line = lab condition, dashed red line = natural condition. All values in decibel units.

Table 3. Averages of the EEG spectral power during the PASAT in both laboratory and natural conditions at sites Fz and Oz for frequency bands theta, alpha and beta.

EEG band	Electrode site	Lab	Natural
Theta	<i>Fz</i>	21.13	20.54
	<i>Oz</i>	20.42	19.83
Alpha	<i>Fz</i>	18.53	17.69
	<i>Oz</i>	20.25	19.76
Beta	<i>Fz</i>	13.69	13.43
	<i>Oz</i>	16.36	16.66

EEG Spectral Power Analysis: PASAT vs Resting Conditions

Finally, statistical comparison of EEG power during the PASAT versus the two resting conditions independently was conducted in order to assess any differences in attentional processing that might exist between the two tasks and how these differences might have been affected by environment. This was achieved via performance of 2x2 repeated measures ANOVAs with factors of Environment and Task (Math, Resting State).

No significant main effects or interaction were found for theta-range power at site Fz when comparing the PASAT to the eyes closed resting state condition: main effect of environment [$F(1,19) = .037, p = .850, n_p^2 = .002$], main effect of task condition [$F(1,19) = .262, p = .615, n_p^2 = .014$], Environment x Task interaction [$F(1,19) = .248, p = .624, n_p^2 = .013$]. Similarly, no significant main effects or interaction were found for theta-range power at site Fz when comparing the PASAT to either the eyes open resting state

condition: main effect of environment [$F(1,19) = .081, p = .778, n_p^2 = .004$], main effect of task condition [$F(1,19) = 3.164, p = .091, n_p^2 = .143$], Environment x Task interaction [$F(1,19) = .334, p = .570, n_p^2 = .017$].

No significant main effect of environment [$F(1,19) = .000, p = .994, n_p^2 = .000$] or interaction [$F(1,19) = .358, p = .557, n_p^2 = .018$] were found for alpha-range power at site Fz when comparing the PASAT to the eyes closed resting state condition. However, there was a significant main effect of task [$F(1,19) = 15.199, p = .001, n_p^2 = .444$] such that significantly lower levels of alpha were observed during the PASAT condition than during the eyes closed condition. No significant main effects or interaction were found for alpha-range power at site Fz when comparing the PASAT to the eyes open resting state condition: main effect of environment [$F(1,19) = .222, p = .643, n_p^2 = .012$], main effect of task condition [$F(1,19) = .415, p = .527, n_p^2 = .021$], Environment x Task interaction [$F(1,19) = .076, p = .786, n_p^2 = .004$].

No significant main effects or interaction were found for beta-range power at site Fz when comparing the PASAT to the eyes closed resting state condition: main effect of environment [$F(1,19) = .500, p = .488, n_p^2 = .026$], main effect of task condition [$F(1,19) = .000, p = .983, n_p^2 = .000$], Environment x Task interaction [$F(1,19) = .270, p = .609, n_p^2 = .014$]. No significant main effects or interaction were found for beta-range power at site Fz when comparing the PASAT to the eyes open resting state condition: main effect of environment [$F(1,19) = .298, p = .591, n_p^2 = .015$], main effect of task condition [$F(1,19) = 1.904, p = .184, n_p^2 = .091$], Environment x Task interaction [$F(1,19) = .193, p = .666, n_p^2 = .010$].

No significant main effects or interaction were found for theta-range power at site Oz when comparing the PASAT to the eyes closed resting state condition: main effect of environment [$F(1,19) = .136, p = .716, n_p^2 = .007$], main effect of task condition [$F(1,19) = 1.688, p = .209, n_p^2 = .082$], Environment x Task interaction [$F(1,19) = 1.061, p = .316, n_p^2 = .053$]. In addition, no significant main effect of environment [$F(1,19) = .430, p = .520, n_p^2 = .022$] or task condition [$F(1,19) = .162, p = .692, n_p^2 = .008$] were found for theta-range power at site Oz when comparing the PASAT to the eyes open resting state condition. However, there was a significant Environment x Task interaction [$F(1,19) = 4.825, p = .041, n_p^2 = .203$]. In the lab, theta band activity at site Oz was significantly higher during the PASAT compared to the eyes open resting state condition [$F(1,19) = 5.881, p = .025, n_p^2 = .236$] whereas in the natural environment theta band activity did not significantly differ between the PASAT and eyes open resting state condition [$F(1,19) = .689, p = .417, n_p^2 = .035$].

No significant main effect of environment [$F(1,19) = .789, p = .385, n_p^2 = .040$] or interaction [$F(1,19) = .110, p = .744, n_p^2 = .006$] were found for alpha-range power at site Oz when comparing the PASAT to the eyes closed resting state condition. However, there was a significant main effect of task condition [$F(1,19) = 27.548, p = .000, n_p^2 = .592$] such that significantly lower levels of alpha were observed during the PASAT condition than during the eyes closed condition. In addition, no significant main effects or interaction were found for alpha-range power at site Oz when comparing the PASAT to the eyes open resting state condition: main effect of environment [$F(1,19) = .606, p = .446, n_p^2 = .031$], main effect of task condition [$F(1,19) = 2.597, p = .124, n_p^2 = .120$], Environment x Task interaction [$F(1,19) = .239, p = .630, n_p^2 = .012$].

Finally, no significant main effects or interaction were found for beta-range power at site Oz when comparing the PASAT to the eyes closed resting state condition: main effect of environment [$F(1,19) = 1.272, p = .273, n_p^2 = .063$], main effect of task condition [$F(1,19) = .000, p = .996, n_p^2 = .000$], Environment x Task interaction [$F(1,19) = .238, p = .631, n_p^2 = .012$]. Also, no significant main effect of environment [$F(1,19) = .846, p = .369, n_p^2 = .043$] or Environment x Task interaction [$F(1,19) = .278, p = .604, n_p^2 = .014$] were found for beta-range power at site Oz when comparing the PASAT to the eyes open resting state condition. However, there was a significant main effect of task [$F(1,19) = 6.454, p = .020, n_p^2 = .254$] such that significantly higher levels of beta were observed during the PASAT condition than during the eyes open condition.

IV. DISCUSSION

The use of spectral power analysis to establish a link between specific EEG frequency bands and specific cognitive tasks has been well studied; however, the effects of manipulations of environment and the presence of distracting stimuli have been largely under studied. The present study sought to establish the first theoretical steps in exploring how environmental factors may influence cognition through the use of a mobile EEG system. In traditional working memory tasks, there is a robust increase in theta and low beta activity in frontal midline sites. This study proposed that when participants are introduced into a natural environment where they must perform a working memory task amid potentially distracting external stimuli there would be a further increase in theta and low beta at frontal midline sites. Our prediction was that participants would be forced to apply more mental resources to the task to overcome the distracting factors and thus frontal activity would increase. We did not see significant changes in EEG spectral power from the lab to the natural environment during the working memory conditions. Additionally, there was no significant change between the lab and natural environments in EEG spectral power during the resting conditions.

To assess environmental effects on brain activity we used a mobile EEG system that could be easily transported from one location to the next without requiring exhaustive logistic measures that would be a factor with a traditional EEG system. Mobile EEG systems are still evolving, and because of their relative newness to the scientific community the range of methodologies used has been limited. In this study, we have been able to utilize mobile EEG to get participants out of the lab and effectively evaluate how certain aspects of cognition function under environmental changes that are

experienced in day-to-day life. Participants ran an auditory numeric processing test called the PASAT, or Paced Auditory Serial Addition Test, in both a laboratory and natural environment. The PASAT involves both executive function and working memory processes which allowed us to draw from previous literature and establish a valid prediction for the EEG band activity we should observe. EEG spectral power was computed via Fast Fourier Transform (FFT) analysis and we observed an increase in overall power across all frequency bands for subjects in the lab environment at frontal midline site Fz. However, paired sample *t*-test analyses showed no significant differences in mean spectral power when lab and natural environments were directly compared. Additionally, scores on a serial addition math task, the PASAT, also did not differ between environments.

Interpretation of the present observations must be tempered by consideration of the limitations of the present study. One limitation was the small sample size. The trend toward spectral power increases in each frequency band observed in the lab may dissipate with an increase in sample size or be exacerbated. At this point the spectral power observations are unclear, and it should be mentioned again that this trend is not statistically significant. A possible explanation is that the distracting stimuli in the natural environment was simply not enough to influence performance. Another criticism of this study is that it has, by its design, low internal validity; that is, the extent to which inferences regarding cause-effect relationships are true within this study. Naturally, because the objective of our study was to evaluate external validity of EEG research, we have sacrificed some control of internal factors. The distracting elements of the natural environment fluctuate greatly. We had no influence over elements of student activity on

campus, noise, weather and time of day. The majority of participants were run during mid-afternoon hours, thus increasing the likelihood of the university campus being active. However, to accommodate for constraints of time to record the target number of participants, not all were run at the same hours of the day. Additionally, we only used one metric to appraise working memory and executive functioning. Using multiple measures to evaluate these cognitive processes could increase the internal validity of spectral power observations if the results are consistent across all task conditions. Future studies with larger sample sizes and multiple task conditions will have a higher likelihood for internal validity. Likewise, the sample was entirely composed of young, college students, who were primarily in their 20s. Their level of education and current practice in quantitative studies could influence for scores on the PASAT.

Although the results were not significant, we did see an overall qualitative increase in EEG power in the laboratory environment during the working memory conditions. As previously stated, a key motivator for the predictions of this study was Kahneman's Attentional Resource Theory. The theory states that the difficulty of a task influences the amount of mental resources that are being used. This theory might help explain the increased power in the sense that in the natural environment, more mental resources are being drawn away to attend to distracting environmental elements and less are able to be applied to the task. The result of this process would lead to an increase in activity in the lab where participants are more able to effectively apply mental resources to the task. However, increased EEG power does not necessarily mean increased cortical activity. In the alpha band cortical activity and activation of that frequency band are often thought of as inversely related (Rana, et al., 2014). Again, it should be reiterated that this

observation of an overall increase in spectral power in the lab is not significant. Additionally, this trend was not seen in the spectral power display computed at posterior site Oz during working memory conditions. Furthermore, if this trend was a representation of some alteration in cognitive processing, we would have observed significant differences on the PASAT when comparing across the lab and natural environments; those statistical comparisons did not yield significant results.

Ongoing resting state EEG was recorded during eyes open and eyes closed conditions at frontal midline site Fz and posterior site Oz in the lab and natural environments for all participants. We ran a series of 2x2 repeated measures ANOVAs to evaluate main effects of environment, resting conditions and any possible interactions. We did not find any significant main effects of environment for theta, alpha or beta frequency bands at frontal midline site Fz or posterior site Oz. The mostly likely explanation for these results is that the environmental changes are not enough to affect mental processes. Perhaps because there are consistent fluctuations in day-to-day environments, the brain effectively adapts and adjusts to these changes. Maintaining homeostasis within the brain during baseline resting states may be an efficient adaptation. If cognition was easily altered by external factors of environment it may be mental taxing and inefficient. However, it should be noted that these interpretations are purely speculative and should not be taken as factual based on our methods.

The resting state findings further validate the results of the math task analysis, demonstrating that cognitive processing does not seem to differ in a laboratory environment versus a natural environment. We did find consistent main effects for resting conditions for all ANOVAs except for when evaluating theta at site Oz. Eyes closed

resting conditions, we found a robust observation of an increase in alpha when compared to eyes open resting conditions. This observation is consistent with previous literature regarding differential brain activity when comparing eyes open versus eyes closed resting states (Adrian & Matthews, 1934; Legewie et al., 1969). Increases in alpha band activity are commonly associated with a reduction in cortical activity, thus during eyes closed resting conditions the brain is less active than eyes open conditions and the reduction in cortical arousal manifests in an increase in alpha. As previously mentioned, irrelevant auditory stimulation attracts attention to its location and trigger a bilateral desynchronization of alpha activity at occipital sites (Störmer et al., 2016). However, our measures of alpha did not change significantly across environments, and the significant increase in alpha activity during eyes closed resting state conditions remained consistent. The brain processes indexed by this contrast in alpha band activity do not change with environment, suggesting that the distracting elements of the natural environment may not have been enough to elicit changes in cortical activity. These observations additionally serve to the credibility to the mobile instrumentation and analysis techniques we have applied. Our system only allowed data from 17 channels to be recorded; thus, there could be a sacrifice in the fidelity of the signal acquisition when compared to traditional 64 electrode EEG systems. However, our analysis is specifically looking at spectral power increases in target frequency bands during certain conditions, and the observed statistically significant increase in alpha during eyes closed resting state conditions supports our methodology. Thus, it is likely that if spectral power differences were to arise because of the manipulation of environment, we likely would have seen them in our recordings.

To reiterate, the goal of the present study was to try and gather data from a more “natural” setting for a participant to see if it differs from the standard observations found in lab environments. However, the null results of this study cannot prove that there is no difference in cognitive processing between environments. That is, there may be differences in cognition between lab and natural environments for these tasks, but the differences are too small to be statistically significant. However, the null results of the study are strong indicators that environmental manipulation has little effect on cognition. Measures of effect size for main effects of environment during resting state conditions show that changes in environment accounted for less than 10% of the variance in EEG spectral power changes across theta, alpha and low beta bands at sites Fz and Oz. Moreover, paired *t*-tests evaluating lab versus natural environments yielded small to moderate effect sizes, calculated via Cohen’s *d*, for changes in EEG spectral power across theta, alpha and low beta bands at frontal site Fz and posterior site Oz. Retained trials for each of the task conditions did not differ significantly when comparing lab versus natural environments, further validating the reliability of the recordings in the natural environment. Additionally, the null findings of this study may be positive news for neuroimaging scientists. If we infer from the current study that robust brain activity for simple tasks, such as working memory, is consistent from laboratory environments to outdoor naturalistic environments, then recording in traditional lab environments could be supported. It is possible that the brain is able to effectively maintain homeostasis even under fluctuation in environmental conditions, and in that regard, using lab environments for neuroimaging recording is externally valid.

The null results of the study also serve to bolster the credibility of minimal mobile systems. The results of this study were able to produce expected changes in EEG spectral power such as the increase in alpha during resting state eyes closed conditions. Additionally, significantly lower levels of alpha were observed during the PASAT compared to the eyes closed resting condition at frontal site Fz and posterior site Oz. This observation is consistent with previous literature regarding alpha desynchronization during working memory tasks (Ray & Cole, 1985). Furthermore, beta band oscillations increased during the PASAT when compared to the eyes open condition at posterior site Oz, which may be an indication that the PASAT was sufficiently stimulating enough to be engaging. A 2x2 repeated measures ANOVA analysis of theta at posterior site Oz yielded a significant Environment x Task interaction such that theta activity significantly increased during the PASAT compared to the eyes open resting state condition in the lab. A possible interpretation of this interaction is that in the lab participants were able to properly focus on the PASAT and utilize working memory effectively, triggering a corresponding increase in theta band activity. It should be noted that our analyses did not show significant increases in theta and beta at frontal site Fz during the PASAT when compared to the lab. This observation is not consistent with previous studies that have observed increases in theta and beta during a working memory task (Dai et al., 2017; Sauseng et al., 2009; Schutte et al., 2017). It is possible that the version of the PASAT implemented in this study was not sufficiently challenging enough to engage working memory mental processes. However, the overall results of these ANOVAs do fall in line with previous literature (Klimesch, 1996; Klimesch et al., 2007; Onton et al., 2005) regarding how theta, alpha and beta can be used to index various mental processes

involved in attention and working memory. These results support the use of minimal mobile systems as they can still be effective tools for neuroimaging even though there is a reduction in signal quality, lack of shielding and a higher risk of artifact contamination.

Human beings operate in a multitude of environments daily, which range drastically regarding the type and concentration of stimuli that is present. This study only evaluated a lab versus an outdoor university campus environment, however, there are many more potential environments that mobile neuroimaging tools could be used to empirically investigate. Technological advances in neuroimaging technologies like mobile EEG present us with opportunities to push psychological research to places it has not gone. This study elected to be one of the first to demonstrate how these technologies can be used in ways that build on previous literature and branch into new areas that remain largely unexplored. Differences in environmental manipulations on cognition are significantly understudied, and thus more research is needed. Future research should further appraise the question of environmental manipulation on cognition and expatiate on the many factors involved in this research topic.

APPENDIX SECTION

Demographic Information Questionnaire:

Date of Birth **Age** **Gender** **Handedness** **Occupation**

Ethnicity (Circle one): Hispanic/Latino, Not Hispanic/Latino

Race (Circle all that apply): African American, Asian, White/Caucasian, Native

American/Alaska Native, Native Hawaiian/Pacific Islander, Other – please specify

Highest Level of education? (circle one): grade school, some HS, graduated HS, trade school, some college, BS/BA, some grad school, MS/MA, JD, PhD, MD, Other. If other, explain

What area of Study?

Years of education (use HS 12; AA 14; BA 16; MA 18; Law 19; PhD/MD 20 or round down!!)

Are you a native English speaker? Yes No

If no, at what age did you begin formal education in English?

Are you fluent in any language(s) other than English? Yes No

If yes, which one(s)?

Do you engage in regular structured physical exercise (more than ½ hour per week)? Yes No

If yes, please indicate:

How many hours per week? On how many days per week?

What do you normally do (please circle)? Running Swimming Weight-Training
Biking Hiking Other (please describe)

Do you play computer/video games more than ½ hour per week? Yes No

If yes, then please indicate:

How many hours per week? On how many days per week?

Please list the names(s) and type (i.e. action, puzzle) of game you play

How did you hear about this experiment?

Would you be willing to be contacted regarding participation in other experiments?

Yes No

Your participation is voluntary, and you are free to decline participation if you wish.

Medical Information

Have you ever had a seizure? Yes No

If yes, when? Do you still have them? How often did you have them? Medications?

Have you ever had a head injury? Yes No

Have you ever lost consciousness? Yes No

If yes to either of the above:

Age?

Circumstances?

Lose consciousness? Y/N If Y, how long?

Hospitalized? Y/N If Y, how long?

Any noticeable changes? (includes headaches)

Y/N If Y, explain.

Have you ever had a neurological disorder or any other problem with your brain or

head? Yes No

If yes, explain:

Have you ever had any surgeries (especially on the heart or head)? Yes No

If yes:

Date

Reason

Amount of Time in hospital

Do you have any problems controlling your movements that would prevent you from being able to write or manipulate small objects? Yes No

If yes, explain:

Do you have any other serious illnesses? Yes No

If yes, explain:

Are you seeing a health care practitioner for any current medical or psychological problems (e.g. depression, anxiety, ADHD)? Yes No

If yes, explain:

Are you taking any medications for these problems or for any other reason (Including vitamins, aspirin, and other regularly taken medications)? Yes No

If yes:

Med Name

Dosage

Prescribed?

Duration of Medication

Reason/Illness

Do you wear glasses or contacts? Yes No

If yes, circle all that apply: regular glasses, bifocals, trifocals, contacts

Are you: near-sighted or far-sighted? (circle one)

Are you color blind? Yes No

If yes, explain:

Do you have cataracts? Yes No

If yes, explain:

How much sleep do you usually need in order to feel rested (in hrs)?

How much sleep did you have prior to this experiment (in hrs)?

Please rate your current physical and mental state on the following scales:

Low/Average/High

Physical _____

Mental _____

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