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Cortical Activation during Mobility in an Indoor Real-World Environment: A Mobile EEG Study

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Kinesiology

Abstract

Human mobility requires neurocognitive inputs to safely navigate the environment. Previous research has examined neural processes that underly walking using mobile neuroimaging technologies, yet few studies have incorporated true real-world methods without a specific task imposed on participants (e.g., dual-task, motor demands). The present study utilized mobile electroencephalography to examine and compare theta, alpha, and beta frequency band power (μV2) in young adults during sitting and walking in laboratory and real-world environments. Our findings support that mobility and environment may modulate neural activity, as we observed increased brain activation for walking compared to sitting, and for real-world walking compared to laboratory walking. Our study highlights the importance and potential for real-world methods to supplement standard research practices to increase the ecological validity of studies conducted in the fields of kinesiology and neuroscience.

Keywords

Mobile neuroimaging, EEG, real-world, mobility, young adults, cognition

Summary for Lay Audience

Walking is important for humans to get from one place to another and explore the surrounding environment. For most people, walking feels automatic and does not require much thought. However, our brain is active during movement, and researchers have tried to examine what is happening in our brain during walking using mobile brain imaging technologies. A primary limitation of previous research is that brain activity during walking has mostly been recorded in a standard laboratory environment. This may be problematic because laboratory environments tend to lack visual and auditory stimuli provided by real-world environments. The few studies that have recorded brain activity in real-world environments have mainly required participants to walk and perform another task at the same time, referred to as a dual-task. For the current study, we were interested in understanding what is happening in the brain during walking in a real-world environment without having participants perform a specific task. 40 young adults completed four conditions while we recorded their brain activity using a mobile headband. The four conditions were as follows: 1) sitting in the laboratory, 2) walking in the laboratory on a treadmill, 3) sitting in an indoor real-world common area on campus, and 4) walking around an indoor real-world common area on campus. In general, we observed higher brain activity during walking compared to sitting. Further, walking in the real-world showed higher brain activity than walking on the treadmill in the laboratory overall. Our results suggest that level of mobility (sitting vs. walking) and environment (laboratory vs. real-world) may impact brain activity. As most research on human movement and brain activity has taken place in a standard laboratory environment, we show the importance and possibility of taking research into the real-world. Using real-world methods to supplement standard practices can provide additional information that is more applicable to the population at large.

Co-Authorship Statement

With guidance and support from Dr. Lindsay S. Nagamatsu, I completed the present research project towards the fulfillment of my master's degree. Under Dr. Nagamatsu's supervision, I designed the research study, carried out data collection, performed data analysis, interpreted the findings, and disseminated the results through this dissertation. I received support from master's students (Gianna Jeyarajan, Raphael Gabiazon) and undergraduate student (Tia Seleem) with data collection. Undergraduate student (Nicholas Hayhow) assisted with data analysis. Data analysis scripts were adapted from Dr. Olav Krigolson.

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Chapter 1

1 Introduction

Mobility is a central component of daily life in humans, allowing us to navigate and interact with the world around us. Walking is a common form of mobility worldwide and is the most popular form of leisure-time activity among Canadians (Statistics Canada, 2015). It is known that walking requires involvement of the central nervous system to execute coordinated movements without continuous attentional resources (Clark, 2015). For decades, researchers have attempted to unveil the specific neurocognitive processes that underly walking through the application of neuroimaging technologies. The minimal literature on brain activity during real walking is likely due to difficulties with recording during movement until recent years. However, despite neuroimaging technologies becoming mobile and less confined to the laboratory environment, few studies have explored the portability of these devices in real-world environments. Most studies have assessed walking using these technologies in a controlled laboratory space or monotonous "real-world" set-up with a focus on dual-tasking (e.g., two tasks performed at the same time) and/or motor demands (e.g., obstacles). The current study examines and compares neural activity among a young adult population during sitting and walking in an indoor real-world environment and controlled laboratory environment using mobile electroencephalography (EEG).

1.1 EEG

1.1.1 Brief Overview

EEG is a non-invasive technique that measures electrical activity of the brain from electrodes applied to the scalp's surface. The most significant source of EEG recording is from large groups of activated neurons in the cerebral cortex that produce synaptic potentials (Olejniczak, 2006). Particularly, pyramidal cortical neurons aligned to the scalp's surface produce electrical field activity, which EEG measures in voltage (Clark, 2009).

1.1.2 History and Applications

A German neurologist named Hans Berger was the first to record human EEG on the scalp in the mid 1920s with a small string galvanometer (Millett, 2001). After making some technical adjustments in the late 1920s, Berger recorded hundreds of EEGs from healthy volunteers and clinical populations (e.g., individuals with epilepsy, skull defects, brain tumors) (Millett, 2001). He observed differences in brain activity across human states (e.g., relaxed vs. alert) and populations (e.g., healthy vs. clinical) (Teplan, 2002). Berger also began to characterize alpha and beta frequencies in his work (Millett, 2001), which are fundamental in EEG analysis today.

EEG has been used extensively for clinical and research purposes since its initial discovery. Soufineyestani and colleagues (2020) describe five broad categories of EEG application: 1) neuroscience and clinical, 2) brain-computer interfaces (BCIs), 3) custom solutions, 4) biometrics, and 5) neuromarketing. A common application of EEG has involved gaining a deeper understanding of brain function and the central nervous system through neuroscience research (cognitive, behavioral, neurophysiological) and clinically for diagnosing brain diseases and impairments (e.g., seizures, coma, sleep disorders). BCIs are another common application that utilize EEG data to control devices, such as governing a virtual reality environment or providing those who are disabled with an alternative method of movement and/or communication. Examples of using EEG for custom solutions applications include for optimal meditative, fitness, or sports performance in individuals. Biometrics, a rather new application of EEG, encompasses the recognition of people through their behavioral or physiological features. EEG data has been used in this way to identify people through unique emotional and cognitive brain functions, for instance. Another new application of EEG is neuromarketing. This involves using EEG to analyze consumer's brain activity in response to an advertisement or product, which may help marketers tailor their outputs towards consumer's needs, feelings, and thoughts.

1.1.3 Frequency Bands

From EEG recordings, we can decompose the recorded signal into different brain waves, also known as frequency bands. These bands are often classified into four groups with approximate spectral ranges: delta (<4 Hz), theta (4–7 Hz), alpha (8–12 Hz), and beta (13–30 Hz) (Clark, 2009). Delta is the highest amplitude and slowest frequency, while beta is the lowest amplitude and fastest frequency, with theta and alpha frequencies falling in the middle of the spectrum. However, for the present study, we will only focus on theta, alpha, and beta.

Theta

Without the imposition of a task or stimulus, referred to as resting state brain activity (Van Diessen et al., 2015), the presence of theta waves is generally indicative of deep relaxation and meditative states in healthy adults (Kumar & Bhuvaneswari, 2012). In non-resting states, theta frequency has been well implicated in learning and memory (Herweg et al., 2020). Accordingly, it makes sense that the hippocampus has been a brain region extensively studied in relation to theta frequency. Increases in theta waves have also been observed during movement and are thought to be involved in visuospatial attention, navigation, and cognitive control, for example (Karakaş, 2020).

Alpha

Alpha frequency is the most dominant frequency band in the human brain and has been extensively researched since its discovery by Hans Berger (Klimesch, 2012). It is well known that alpha waves occur in the resting state when healthy adults are awake with their eyes closed but reduces significantly during eyes open conditions (Berger effect) (Kirschfeld, 2005). In the non-resting state, alpha has been linked to a broad range of neurocognitive functions in different brain areas, including visual, auditory, prefrontal, and sensorimotor regions (Clayton et al., 2018). In the visual realm, for example, recent evidence suggests that alpha plays five distinct roles: 1) the inhibitor, 2) the predictor, 3) the perceiver, 4) the communicator, and 5) the stabilizer (Clayton et al., 2018). Although

alpha has mostly been studied while participants are stationary, there is some evidence to suggest that alpha may be suppressed during walking (e.g., Cao et al., 2020).

Beta

In the resting state, beta waves tend to dominate when one is alert, actively thinking, and focused (Kumar & Bhuvaneswari, 2012). In the non-resting state, increases in beta have been observed during tasks of decision making, working memory, language processing, and visual perception, for example (Spitzer & Haegens, 2017). However, beta waves have been predominately linked to sensorimotor and basal ganglia structures, where studies have shown an increase in beta when preparing to make a movement, a decrease during movement execution, and a "rebound" after movement execution (Barone & Rossiter, 2021; Kilavik et al., 2013; Spitzer & Haegens, 2017). Yet, the exact role of beta frequency remains unclear, with studies reporting discrepant findings; leading researchers to propose that beta may play several roles in the human brain that require further investigation (Spitzer & Haegens, 2017).

1.1.4 Advantages and Disadvantages

One of the most advantageous aspects of EEG is high temporal resolution or the ability to measure rapidly changing brain activity in a timely manner (Luck, 2014). In this way, EEG is superior to other neuroimaging techniques that do not offer as high temporal resolution (e.g., functional near-infrared spectroscopy [fNIRS], functional magnetic resonance imaging [fMRI], positron emission tomography [PET]) (Lau-Zhu et al., 2019). Many researchers observe brain activities generated in response to certain external or internal stimuli, known as event-related potentials (ERPs) (Luck, 2014). EEG captures ERPs with millisecond precision, allowing researchers to investigate specific perceptual, sensory, and cognitive processing (Luck, 2014). EEG equipment is generally lower in cost and easier to use compared to other techniques (e.g., fMRI, PET). EEG additionally benefits from non-invasive procedures that can be used with populations of all ages and individuals that are unable to make motor responses or respond to stimuli, such as comatose patients.

Although EEG is useful for measuring when brain activity occurs, a main limitation is its ability to measure where the source of the activity is coming from in the brain. This is termed the “inverse problem” and has received extensive attention from researchers attempting to distinguish the underlying sources of EEG signal (Awan et al., 2019). As well, since EEG picks up signals from a large population of activated neurons, it is not sensitive enough to measure activity from small groups or singular neurons (Olejniczak, 2006). In other words, elicited brain activity will not be captured by EEG systems if the signal is not strong enough to register.

Another notable limitation of EEG is that it may be subject to high noise from normal human movement and processes. This means that undesirable activity other than cortical activity can be picked up by the EEG and present itself in our data, known as artifacts (Urigüen & Garcia-Zapirain, 2015). Common causes of artifacts in EEG data include eye blinks, jaw clenches, head movements, and cardiac activity (Urigüen & Garcia-Zapirain, 2015). Arguably, however, EEG is more forgiving to movement than other functional neuroimaging techniques, such as fMRI. There are also methods that can be undertaken during analysis to identify and remove artifacts from data (Urigüen & Garcia-Zapirain, 2015) but the prevention of artifacts in the first place is ideal.

1.1.5 Traditional vs. Mobile

Traditional EEG systems involve electrodes placed on the scalp, often with conductive material, such as gel. The electrodes are connected by wires to equipment, including an amplifier and converter so that the signals can be multiplied for processing and digitalization. Due to physical limitations of traditional EEG, participants are often confined to the laboratory space. Mobile neuroimaging technologies make it possible to observe more realistic human behaviors in and outside of the laboratory. In other words, mobile EEG allows for novel aspects of mobility at the level of the system and person (Lau-Zhu et al., 2019). The level of mobility varies between systems, with some requiring equipment to only be placed on the head, while others require a headset and a backpack to carry the rest of the equipment (Bateson et al., 2017). Regardless, mobile EEG systems tend to be battery-powered, small, and lightweight with no wire

attachments (Janssen et al., 2021). In addition, many mobile EEG systems do not require the use of conductive material and utilize dry electrodes (Lau-Zhu et al., 2019). In contrast, traditional EEG requires time consuming preparation and cleaning of materials to ensure that there is no build-up that can impact signal quality.

There are a few disadvantages of mobile EEG that should be discussed. Mobile EEG systems tend to have fewer electrodes (Janssen et al., 2021), which limits the amount of data that can be recorded at any given time from different areas of the scalp. Although mobile systems do allow for greater mobility in different environments, this can be problematic when artifacts taint collected data. This may result in more data being excluded from analysis than what is typical from traditional EEG and should urge researchers who use mobile systems to increase their recording time or number of trials to account for expected data loss (Janssen et al., 2021).

1.2 Evidence from Neuroimaging Studies on Real Walking

1.2.1 Literature Published Before 2015

Hamacher and colleagues (2015) conducted a systematic review to compile the literature on brain activity and walking. Twenty-three studies examining real walking were included in the review. Findings from healthy adults largely demonstrated increased brain activity during walking (compared to sitting and/or standing) in a plethora of cortical and subcortical regions including the frontal cortex, prefrontal cortex, visual cortex, sensorimotor areas, parietal cortex, pre-supplementary motor area, supplementary motor area, pre-motor area, M1, cerebellum, pons, basal ganglia, occipital lobule, anterior cingular cortex, and temporal lobe. Conversely, few studies reported decreased activity in regions of the brain during walking (e.g., La Fougere et al., 2010; Shimada et al., 2013).

Dual-tasking is often studied in relation to brain activity during walking, as illustrated by the studies included in this review. Dual-tasking involves the performance of two tasks at the same time, such as a motor task (e.g., walking) and cognitive task (e.g., counting by threes backwards), two motor tasks (e.g., walking and holding a glass of water), or two cognitive tasks (e.g., counting backwards by threes and counting auditory tones) (Pashler, 1994). Dual-task walking often includes a cognitive task that measures executive

functioning or a component of it. Executive functioning is a multidimensional cognitive process that encompasses various abilities involving goal-directed behavior, such as decision making, task-switching, and inhibiting (Banich, 2009). One such ability linked to executive functioning that is often studied during dual-task walking is attention. The cognitive process of attention allows us to position and orient ourselves to relevant stimuli (Posner & Boies, 1971). In everyday life, we are presented with stimuli from the environment around us and from within ourselves. Our attention controls what stimuli we pay attention and respond to (McDowd & Birren, 1990).

Most dual-task studies included in the review demonstrated that young adults displayed higher prefrontal activity during dual-task walking. Few studies found a decrease or no difference in prefrontal activity under dual-task walking conditions among young adults. One study found that the communication of non-sensorimotor areas was increased during dual-task walking (Lau et al., 2014).

Overall, this systematic review highlighted the need for additional neuroimaging studies to be conducted during walking in adults. Studies included in the review utilized diverse methodical approaches and reported various cortical and subcortical activations during walking. In addition, although some mobile neuroimaging techniques were utilized in studies included in the review (EEG-based Mobile Brain and Body Imaging [MoBI], fNIRS), all walking occurred in a controlled laboratory setting. This prompts the question – how applicable are these findings to real-life scenarios?

1.2.2 Literature Published 2015 and After

Due to restrictions of traditional neuroimaging techniques and the desire to examine brain activity during real walking, the use of mobile techniques became more prominent in neuroimaging studies. Therefore, we will first review mobile neuroimaging studies conducted in the laboratory (e.g., treadmill walking, overground/floor walking). Second, we will discuss mobile neuroimaging studies conducted outside of the standard laboratory environment (e.g., corridor walking, outdoor walking). In the next section, the gap in the literature will be identified, the rationale for conducting the current study will be explained, and an overview of the present thesis will be provided.

Mobile neuroimaging and walking in the laboratory (EEG)

Beurskens and colleagues (2016) examined the neural correlates of single and dual-task walking in 12 young adults using a 64-channel mobile EEG system. Both cognitive (Go/NoGo task) and motor interference (task involving sticks and rings) tasks were applied separately to observe effects on walking. Walking was performed on a 10-meter instrumented walkway. The results demonstrated significant modulations in alpha and beta frequencies in cognitive and motor dual-task walking. Both dual-task conditions showed lower alpha in the frontal and central regions, but for the motor dual-task, increased beta was also observed in the frontal region. Decreased beta was observed in the central regions during cognitive interference walking.

Similarly, a recent study by Vandenheever and Lambrechts (2023) of 10 young adults assessed brain activity using a BRAIN Products ActiCAP mobile EEG system while participants walked on a treadmill and performed the Flanker test, a measure of selective attention and inhibitory function (Eriksen & Eriksen, 1974). Like what was found in the previous study during cognitive interference walking, average alpha and beta frequencies decreased during dual-task walking. The study also found larger P3 amplitudes and longer latencies for dual-task walking compared to standing.

Another study of dual-task treadmill walking utilized MoBI to assess brain activity in a sample of 22 young adults (Richardson et al., 2022). Recording took place as participants sat and walked while performing a cued task-switching paradigm. The results indicated that walking altered neural responses during proactive and reactive control as the task became more difficult. Amplitude of target evoked parietal P3 and fronto-central N2 were reduced and increased cue-evoked late frontal slow waves were observed during walking.

Another study used a 32-electrode cap connected to a portable amplifier to examine and compare brain activity during obstacle avoidance and obstacle free walking in a sample of 32 young adults (Mustile et al., 2021). The results showed neural markers during obstacle avoidance, observed through increases in frontal theta power (proactive – before obstacles) and centro-parietal beta power (reactive – after obstacles). The authors

concluded that the proactive findings suggest the updating of motor plans as soon as the obstacle appears, and the reactive findings suggest the resetting of the motor system after the obstacle is crossed.

Mobile neuroimaging and walking in the laboratory (fNIRS)

fNIRS is a non-invasive neuroimaging technique that measures changes in oxygenated hemoglobin concentration, allowing for the observation of active brain regions during a certain event or task (Chen et al., 2020). Compared to EEG, fNIRS provides strong spatial resolution but suboptimal temporal resolution (Chen et al., 2020).

Findings from studies employing fNIRS during dual-task walking in the laboratory have found an increase in PFC activity. For instance, St George and colleagues (2022) measured PFC activity in young and older adults during five standing and walking conditions. Reciting Alternate Letters of the alphabet (RAL) and serial subtraction by threes (SS3) were used to measure cognitive inhibition and working memory, and working memory alone, respectively. Walking took place on an electronic walkway. For younger adults, PFC activity decreased during normal walking (single task) compared to standing but increased during dual-task walking with a greater increase for RAL than SS3.

Similarly, we see increases in PFC activation while participants perform non-straight dual-task walking. Belluscio and associates (2021) examined brain activation of 20 young adults during single and dual-tasks while they walked linearly or curvilinearly in laboratory. As walking is not always straight in the real-world, this study brings a unique perspective that provides more representation for real-life situations. The cognitive task was the “Serial 7s” test; a measure of information processing speed (Williams et al., 1996). The findings indicated increased PFC activation during walking along the curvilinear path during dual-tasking.

Furthermore, Kvist and colleagues (2023) found activation of the PFC in adults when engaged in dual-task walking and navigation. The study included two dual-task walking protocols in laboratory using cones: 1) straight walking while performing the auditory

Stroop task and 2) navigated walking while performing the Stroop task. The Stroop task is a cognitive interference task that assesses selective attention (Bench et al., 1993).

Although few, some studies have not found an increase in PFC activation during dual-task walking. For instance, Stuart and associates (2019) observed cortical activity using fNIRS during dual-task treadmill walking in 17 young and 18 older adults and observed the effects of cognition (digit vigilance task) on cortical activity changes. Across groups, the study found increased cortical activity during dual-task walking in the supplementary motor area, premotor cortex, and the primary motor cortex (motor regions) but not in the PFC (cognitive region). Other studies have found lower activation of the PFC during dual-task walking compared to normal walking (e.g., Lin & Lin, 2016).

Mobile neuroimaging and walking outside the laboratory

Pizzamiglio et al (2018) observed brain activity in 14 young adults using a 64-channel Waveguard cap mobile EEG system while participants walked around a path on the university campus and 1) texted with their smartphone and 2) conversed with the experimenter. Brain activation was also recorded in the absence of a dual-task while participants walked freely around campus. The study aimed to investigate how brain regions may predict walking in a real-world environment during dual-tasking using a predictive model. The authors concluded that trunk acceleration displayed a positive predictive relationship with left posterior parietal cortex (PPC) theta power in the free walking condition and the left PPC alpha power in the walking while talking condition. In opposition, a negative predictive relationship was found between trunk acceleration and left PPC beta power in the walking while texting condition. The study suggested that the left PPC may be implicated in gait control and sensorimotor integration in real-world walking.

Multiple studies have assessed attention using the auditory oddball task during dual-task walking. In one study (Ladouce et al 2019), a 32-electrode system with a portable amplifier was used to observe the P3 effect while walking up and down a corridor. The first experiment showed a reduction in attention while walking compared to standing. The second experiment illustrated that decreased attention was found to be similar during

walking and being wheeled down the corridor in a wheelchair. The authors suggested that it may not be the act of walking causing this attentional decrease but motion in general. Through isolating visual and inertial stimulation, the third experiment demonstrated that visual and inertial stimuli contribute independently to attentional mechanisms during motion and that the sum of these processing demands contribute to observed declines in attention during walking.

In another study employing the auditory oddball task, Reiser and colleagues (2019) utilized a 30-electrode cap connected to a portable amplifier to examine the neural underpinnings of cognitive-motor dual-tasking while standing, walking, and partaking in an obstacle course outdoors. The study revealed a decrease in frontal midline theta power and in parietal P3 amplitude with greater motor complexity.

Likewise, brain activity was recorded across 44 adults exposed to an auditory oddball task using 32 electrodes connected to an amplifier during three conditions: 1) sitting in laboratory, 2) walking/navigating campus, and 3) walking around a sports field (Liebhurr et al 2021). Results revealed that attention was reduced in the walking around campus condition. Furthermore, ERPs obtained for the real-world conditions differed significantly from the laboratory condition.

Protzak and colleagues (2021) examined ERPs (early P1 and later P3) using MoBI in younger and older adults while sitting, standing, and walking up and down a corridor while performing a visual stimulus-response task. In the younger group, the results revealed that during the walking condition, inaccuracies with the task and slower responses were associated with reduced P1 amplitudes and prolonged latencies. Prolonged P3 latencies were also present as the motor task became increasingly difficult.

In another study of walking in a corridor area (Asahara et al., 2022), fNIRS was used to examine regional PFC activity in 14 young adults. The study found that activation increased in the ventrolateral PFC (VLPFC), dorsolateral PFC (DLPFC), and lateral frontopolar cortex (FPC) before walking, but differed during the actual act of walking. Activation further increased in the ventrolateral PFC, but decreased in the dorsolateral PFC, and lateral and medial FPC. In addition, the authors increased cognitive demand

during walking by depriving visual feedback. This counteracted the observed decrease in the dorsolateral PFC and lateral and medial FPC. The authors concluded that there may be functional distinction of the PFC during walking, where the observed increase during walking is likely a unique response of the ventrolateral PFC and that regional activation differed with cognitive demand.

Overall, from the literature presented above, findings generally support significant modulations in neural activity during walking with dual-task and motor demands in young adults. This may suggest that additional influences are being placed on cognitive resources during walking, compared to sitting or standing. Previous literature also draws light on the surrounding environment (e.g., obstacles, path shape, outdoor stimuli) and how brain function and cognition may differ across settings.

1.3 Overview of Thesis

Despite the abundance of published neuroimaging research on walking in young adults, the presented literature supports that we have a limited understanding of neurocognitive processes during walking beyond controlled environments, specifically non-dual-task walking. Previous work has primarily been conducted in the laboratory or in a monotonous “real-world” environment, with few studies venturing into a true real-world setting. We argue that further understanding of cortical activity during walking requires immersion into a real-world environment that incorporates rich environmental stimuli (e.g., architecture, color, sounds, people, path curves). The few studies that have ventured outside of the laboratory into real-world environments (e.g., walking outdoors around a university campus) have imposed a specific task on participants (e.g., dual-task, motor demands) during walking. This does not allow for a deeper understanding of what is occurring in the brain in the absence of these imposed tasks. Using the auditory oddball task as an example, this requires participants to wear headphones to hear auditory tones during the task. As a result, this may limit the auditory experience from the environment (e.g., other sounds, noise), which may have additional influences on cognitive and attentional resources otherwise.

To our knowledge, no study has yet observed brain activity during walking in a true real-world environment without the imposition of a secondary task and compared findings to standard laboratory conditions. Therefore, we conducted a within-subjects study to examine neural processes of young adults during sitting and walking in an indoor real-world environment and compared these findings to sitting and walking in a standard laboratory environment. The indoor real-world environment utilized in this study is a centralized common space in a building on our university's campus that includes a living green wall, an abundance of natural light, and is often populated by people sitting, walking, and talking. We recorded brain activity during four conditions using the Muse S brain sensing headband. We analyzed and compared theta, alpha, and beta power across conditions. The independent variables for this study were environment (laboratory vs. real-world) and mobility (sitting vs. walking) and the dependent variable was EEG power.

We predicted that there would be significant differences in band power across conditions. Regarding the specific frequency bands, we hypothesized that theta power would increase during walking compared to sitting and in the real-world environment compared to the laboratory, as theta waves have been linked to movement, attention, and spatial navigation (Karakaş, 2020). We also speculated that beta power may increase in the real-world environment compared to the laboratory in the absence of a specific cognitive task, as participants would likely be more alert and attentive to additional environmental stimuli provided by the real-world condition. However, as beta waves have been shown to differ before, during, and after walking (Barone & Rossiter, 2021; Kilavik et al., 2013; Spitzer & Haegens, 2017), we were unclear if we would observe any differences in beta power across sitting and walking conditions. Regarding alpha power, we hypothesized a decrease during walking, as some previous laboratory studies have supported a walking-induced alpha decrease (e.g., Cao et al., 2020). However, we were unclear about whether there would be a difference in alpha power between the laboratory and real-world environment, as alpha has been implicated in various processes, such as the inhibition of certain visual information and in brain region communication, for example (Clayton et al., 2018).

Chapter 2

2 Methods

2.1 Participants

A sample of 40 university students were recruited for this study. Young adults were included if they met the following criteria: 1) have normal or corrected-to-normal visual and auditory acuity; 2) are 18-30 years of age; 3) can walk independently; 4) are right-handed; 5) can read and write in English; and 6) have no history of neurological impairment, neuropsychiatric disorder, or eye injury. Participants were excluded if they were currently taking psychotropic medication or have a medical condition or other limitation that prevents them from walking unassisted.

This study was approved by the Non-Medical Research Ethics Board (NMREB) at Western University (see Appendix A). All participants provided written informed consent before participating in the study.

2.2 Design and Conditions

We utilized a within-subjects study design, where each participant completed all four conditions (**Figure 1**). We randomized which environment participants started with (laboratory or real-world) to reduce the back and forth between the two environments. Participants completed both conditions (sitting and walking) in one environment before moving to the next. Please see examples of the condition order below.
Example 1. laboratory sitting, laboratory walking, real-world sitting, real-world walking.
Example 2. real-world sitting, real-world walking, laboratory walking, laboratory sitting.
Example 3: laboratory walking, laboratory sitting, real-world walking, real-world sitting.

2.2.1 Laboratory Sitting Condition

Participants were seated in the fitness laboratory (Thames Hall 2100, Western University) for five minutes. The chair was positioned to face the wall where the blinds were drawn so that activity outside of the laboratory could not be observed. The participants were

instructed to sit with their eyes open while their brain activity was recorded. The researcher(s) sat silently out of sight from the participants.

2.2.2 Laboratory Walking Condition

Participants walked on a treadmill in the fitness laboratory (Thames Hall 2100, Western University) for 10 minutes. The treadmill was positioned to face the wall where the blinds were drawn so that activity outside of the laboratory could not be observed. The participants were instructed to walk facing forward at a comfortable and leisurely pace that would not exhaust them or cause them to sweat excessively while their brain activity was recorded. The researcher(s) sat silently out of sight from the participants.

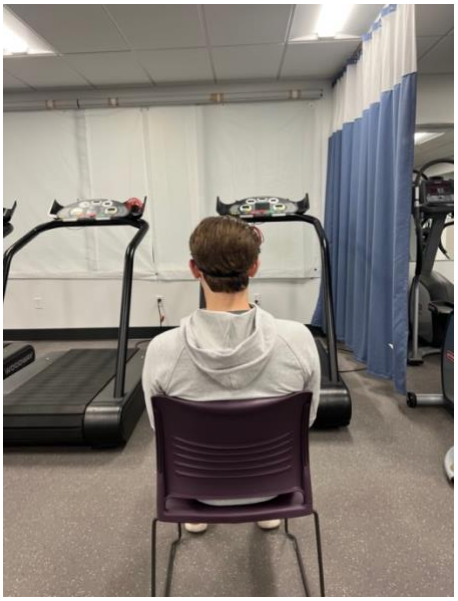
2.2.3 Indoor Real-World Sitting Condition

Participants were seated in a common area on the first floor of Thames Hall, Western University for five minutes. This indoor space includes a living green wall, an abundance of natural light, and is often populated by people sitting, walking, and talking. The participants were instructed to sit with their eyes open while their brain activity was recorded. The researcher(s) sat quietly out of sight from the participant.

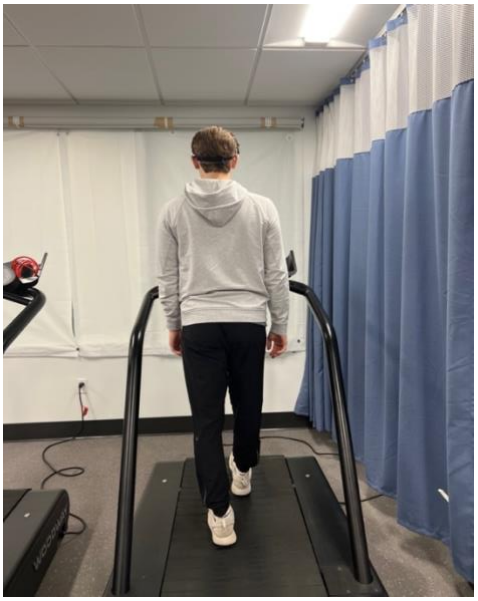
2.2.4 Indoor Real-World Walking Condition

Participants walked around the first floor of Thames Hall, Western University for 10 minutes. This walk included large hallways lined by offices, study rooms, and lockers. Participants also walked through the space with the living green wall and natural light. In this condition, participants often walked by people sitting, walking, and talking. Each participant followed the same route. They were instructed to walk facing forward at a comfortable and leisurely pace that would not exhaust them or cause them to sweat excessively while their brain activity was recorded. The researcher(s) followed closely behind the participant but out of sight to ensure that EEG Bluetooth connection was maintained throughout the condition.

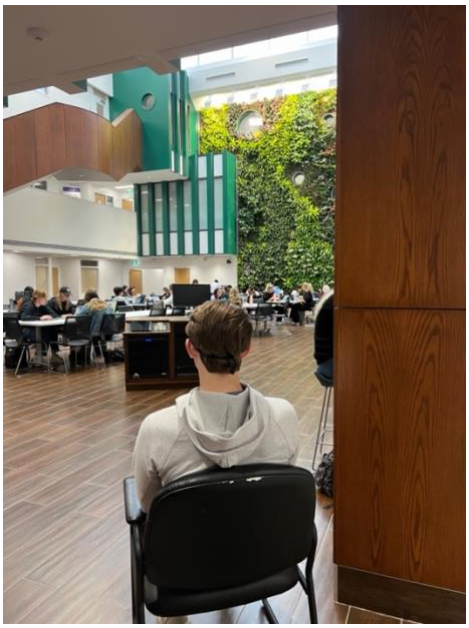
A. Laboratory sitting condition



B. Laboratory walking condition



C. Indoor real-world sitting condition



D. Indoor real-world walking condition

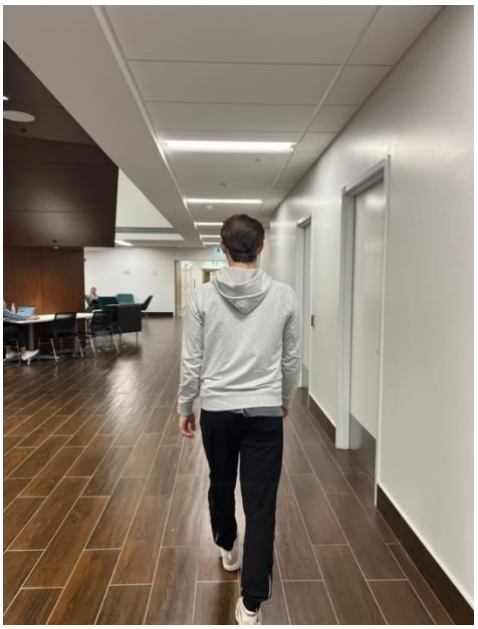


Figure 1. Four conditions completed by participants during EEG recording.

2.3 Procedure

Recruitment took place from August 2022 to May 2023. Participants were recruited from advertisements posted around Western University campus, in the London community, on the Exercise, Mobility, and Brain Health Lab's social media accounts (Instagram, Facebook, Twitter), and on approved course sites. The study was also advertised to all current students through Western's mass e-mail system towards the end of the recruitment period. Individuals interested in participating in the study were prompted to contact Samantha Marshall or Dr. Lindsay Nagamatsu through e-mail or telephone.

Upon contact from potential participants, eligibility for study inclusion was confirmed and the study Letter of Information was sent to provide more information about the study details and the location (Thames Hall, Western University). A time was then scheduled at the individual's convenience to come into the laboratory for the research session. All participants were asked to wear comfortable clothes and shoes for walking, to refrain from wearing any makeup, sunscreen, or moisturizer on their forehead, as this is where the EEG will be placed, and to bring a hair tie if they have long hair.

When participants arrived at the laboratory, they underwent the formal informed consent process, and any questions were answered by the researcher. After consent was acquired, participants completed the demographic questionnaire and the depression, anxiety, and stress scale (DASS-21) (see Appendix B).

Participants were then prepped and fitted with the mobile EEG headband. Prepping entailed wiping the participant's forehand and behind their ears with an alcohol swab, as this is where the electrodes were placed. Participants with long hair were asked to put their hair up at this time. Before fitting, a small amount of water was applied to the electrodes on the headband to increase the quality of the EEG signal. The headband was then expanded or condensed to properly fit the participant's head size. The researcher checked to ensure that each electrode had a snug fit against the skin and that participants were comfortable with the headband placement. The headband was then calibrated to ensure that the sensors achieved a good signal quality before beginning the first condition.

Each participant completed all four conditions. After each condition, they were prompted to reflect and write down what they were thinking about during the condition (see Appendix B for mind wandering questionnaire). After completion of the study, participants were asked if they had any questions and were thanked for participating.

2.4 Mobile EEG Recording and Analysis

Brain activity was recorded using the Muse S Generation 2 Brain-Sensing Headband (https://choosemuse.com/products/muse-s-gen-2). We chose to use this mobile EEG system in our study because it is accessible, cost-effective, and comfortable for participants to wear without imposing on their natural movements in each environment. Importantly, this EEG system has been validated as a viable tool for research purposes (Krigolson et al., 2021).

The Muse is equipped with four dry electrodes: two frontal (AF7 and AF8) and two temporal (TP9 and TP10). A reference sensor (FpZ) is located on the center of the headband and is placed on the middle of the forehead. Via Bluetooth connection to the Muse, EEG data were collected on an iPhone 11 using the Mind Monitor application at a sampling rate of 256 Hz. Created by James Clutterbuck, Mind Monitor is used exclusively with the Muse but is not an official Muse application (https://mind-monitor.com/#page-top). Raw EEG data for each condition were directly uploaded to Dropbox as a CSV file.

The data were then imported into MATLAB (R2022a). Using scripts adapted from Dr. Olav Krigolson (https://www.krigolsonlab.com/muse-analysis.html), we processed the data. The scripts read the imported Mind Monitor data and converted it into EEGLAB format where it was demeaned and detrended. Data were filtered using a 0.1 Hz high pass, a 30 Hz low pass, and a 60 Hz notch filter. 1000ms epochs with a 500ms time window overlap were extracted from the continuous data. Artifacts were removed from the segmented data, which involved taking the difference between the voltage minimum and maximum and comparing it against a rejection threshold. The threshold was determined on an individual participant basis to optimize artifact rejection for each participant. Next, Fast Fourier Transform (FFT) analysis was performed to obtain

specific frequency bands for each electrode. We defined theta as 4-7 Hz, alpha as 8-12 Hz, and beta as 13-30 Hz. We displayed key numerical summary information, including artifact numbers and output band power per electrode. We plotted the outputs for each of the four electrodes by condition, with Frequency (Hz) on the x axis and Power (uV^2) on the y axis to better visualize the data. Examining power is useful to identify which frequency bands are most prominent in the data (Pivik et al., 1993). As preliminary analysis revealed no lateralized effects, we averaged the outputs from the AF7 and AF8 electrodes to obtain a pooled frontal electrode average. The same was done for TP9 and TP10 to obtain a pooled temporal electrode average. Relevant data were extracted in an Excel spreadsheet file and statistical analysis was conducted thereafter.

2.5 Quantitative Data and Statistical Analysis

All data were imported via Excel file into SPSS Statistics (version V29 for Mac). Descriptive statistics were used to characterize the participant data. The full sets of EEG data (i.e., participants with data for all four conditions) were analyzed using 2 x 2 repeated measures ANOVA with within subject factors of environment (laboratory vs. real-world) and mobility (sitting vs. walking). As main effects were observed, simple main effects were analyzed thereafter to determine any differences at each level of our independent variables. Data normality was inspected visually (histograms, box plots) and using the Shapiro–Wilk test. Any dependent variables that were found to violate the assumption of normality underwent log transformation to conform the data to an approximately normal configuration. Significance was set to $p \leq .05$ for all statistical analyses. Effect sizes (partial eta squared, ηp^2) are reported with an interpretation of small = 0.2, medium = 0.5, and large = 0.8.

2.6 Qualitative Data Extraction and Analysis

Data from the mind wandering questionnaires were extracted verbatim into an Excel spreadsheet file and organized according to the four conditions. Braun & Clarke's (2006) six-step framework for conducting a thematic analysis was followed. First, three researchers examined the data for each condition independently. Second, the data were re-visited by each researcher and initial codes were created to begin organizing the data.

Third, each researcher reviewed their initial codes and identified overarching patterns or themes. Fourth, the researchers came together to review and compare the themes that they had identified. Fifth, themes were agreed upon and defined by the researchers as a group. Sixth, the results were written-up to describe and compare the main themes identified in the mind wandering questionnaires across conditions.

Chapter 3

3 Results

3.1 Participant Characteristics

Descriptive characteristics of our sample are provided in **Table 1**. 40 young adults between the ages of 18 and 28 years participated in the study. 24 participants were biological females and self-identified as women. The remaining 16 participants were biological males and self-identified as men. 10 participants scored above normal on the anxiety component of the DASS-21 (6 mild, 3 moderate, 1 severe; 5 female). Seven participants scored above normal on the stress component of the DASS-21 (1 mild, 4 moderate, 2 severe; 6 female). Three participants scored above normal on the depression component of the DASS-21 (2 mild, 1 severe; 2 female).

3.2 EEG Frequency Band Power

A 2 x 2 repeated measures ANOVA with within subject factors of environment and mobility was conducted with 17 full participant datasets (see **Tables 2, 3, and 4**). Participants with missing or unusable data for one or more conditions were not included in the statistical analysis (n=23). Reasons for condition exclusion included: 1) the presence of high artifacts, specifically in the walking conditions (n = 16); 2) a MATLAB error when attempting to run the data (n = 4); and 3) an issue with the data uploading to Dropbox (n = 3). The data were examined for outlier values > ±3 standard deviation from the mean, but none were present.

Table 1. Participant characteristics

N	40
Age M (SD)	22.60 (2.63)
Sex No. female (%)	24 (60%)
Gender	24 women, 16 men
DASS-21	
Depression No. (%) scoring above normal	3 (7.5%)
Anxiety No. (%) scoring above normal	10 (25%)
Stress No. (%) scoring above normal	7 (17.5%)

Table 2. Mean frequency band power (μV2) across conditions

	Lab sitting M (SD)	**Lab walking M (SD)**	**Real-world sitting M (SD)**	**Real-world walking M (SD)**
Theta (frontal)	1.104 (0.561)	4.002 (3.264)	1.408 (0.658)	8.314 (10.245)
Theta (temporal)	5.548 (3.477)	12.148 (8.524)	3.892 (2.499)	24.647 (23.026)
Alpha (frontal)	0.704 (0.397)	1.680 (1.142)	0.951 (0.458)	2.585 (2.554)
Alpha (temporal)	2.728 (1.910)	4.601 (3.310)	2.552 (1.598)	7.640 (6.133)
Beta (frontal)	0.972 (1.099)	0.793 (0.612)	1.025 (1.092)	1.088 (0.860)
Beta (temporal)	0.881 (0.651)	1.225 (0.648)	1.053 (0.576)	1.988 (1.515)

Table 3. Within-subjects repeated measures ANOVA - log10 transformed

	Factor	**F**	**df**	**ηp^2**	***p*-value**
Theta (frontal)	Environment	6.615	1, 16	.293	.020*
	Mobility	56.429	1, 16	.779	<.001*
	Environment x Mobility	.171	1, 16	.011	.685
Theta (temporal)	Environment	.806	1, 16	.048	.383
	Mobility	90.565	1, 16	.850	<.001*
	Environment x Mobility	16.098	1, 16	.502	.001
Alpha (frontal)	Environment	7.070	1, 16	.306	.017*
	Mobility	32.786	1, 16	.672	<.001*
	Environment x Mobility	.037	1, 16	.002	.850
Alpha (temporal)	Environment	2.044	1, 16	.113	.172
	Mobility	25.841	1, 16	.618	<.001*
	Environment x Mobility	5.817	1, 16	.267	.028
Beta (frontal)	Environment	5.909	1, 16	.270	.027*
	Mobility	2.356	1, 16	.128	.144
	Environment x Mobility	.206	1, 16	.013	.656
Beta (temporal)	Environment	5.359	1, 16	.251	.034*
	Mobility	12.491	1, 16	.438	.003*
	Environment x Mobility	.399	1, 16	.024	.537

* Significant at the .05 level.

Table 4. Simple main effects statistical results – log10 transformed

	Within factor comparison	**Mean difference (A vs. B)**	**Standard error**	***p*-value**
Theta (frontal)	Laboratory sitting (A) vs. walking (B)	-.476	.091	<.001*
	Real-world sitting (A) vs. walking (B)	-.550	.130	<.001*
	Laboratory (A) vs. real-world (B) sitting	-.100	.053	.077
	Laboratory (A) vs. real-world (B) walking	-.173	.137	.224
Theta (temporal)	Laboratory sitting (A) vs. walking (B)	-.307	.077	.001*
	Real-world sitting (A) vs. walking (B)	-.716	.071	<.001*
	Laboratory (A) vs. real-world (B) sitting	-	-	-
	Laboratory (A) vs. real-world (B) walking	-	-	-
Alpha (frontal)	Laboratory sitting (A) vs. walking (B)	-.327	.073	<.001*
	Real-world sitting (A) vs. walking (B)	-.301	.097	.007*
	Laboratory (A) vs. real-world (B) sitting	-.135	.035	.001*
	Laboratory (A) vs. real-world (B) walking	-.110	.108	.327
Alpha (temporal)	Laboratory sitting (A) vs. walking (B)	-.187	.069	.016*
	Real-world	-.416	.082	<.001*

	sitting (A) vs. walking (B)			
	Laboratory (A) vs. real-world (B) sitting	-	-	-
	Laboratory (A) vs. real-world (B) walking	-	-	-
Beta (frontal)	Laboratory sitting (A) vs. walking (B)	-	-	-
	Real-world sitting (A) vs. walking (B)	-	-	-
	Laboratory (A) vs. real-world (B) sitting	-.085	.059	.166
	Laboratory (A) vs. real-world (B) walking	-.125	.065	.071
Beta (temporal)	Laboratory sitting (A) vs. walking (B)	-.172	.048	.002*
	Real-world sitting (A) vs. walking (B)	-.224	.086	.020*
	Laboratory (A) vs. real-world (B) sitting	-.109	.065	.113
	Laboratory (A) vs. real-world (B) walking	-.161	.078	.055

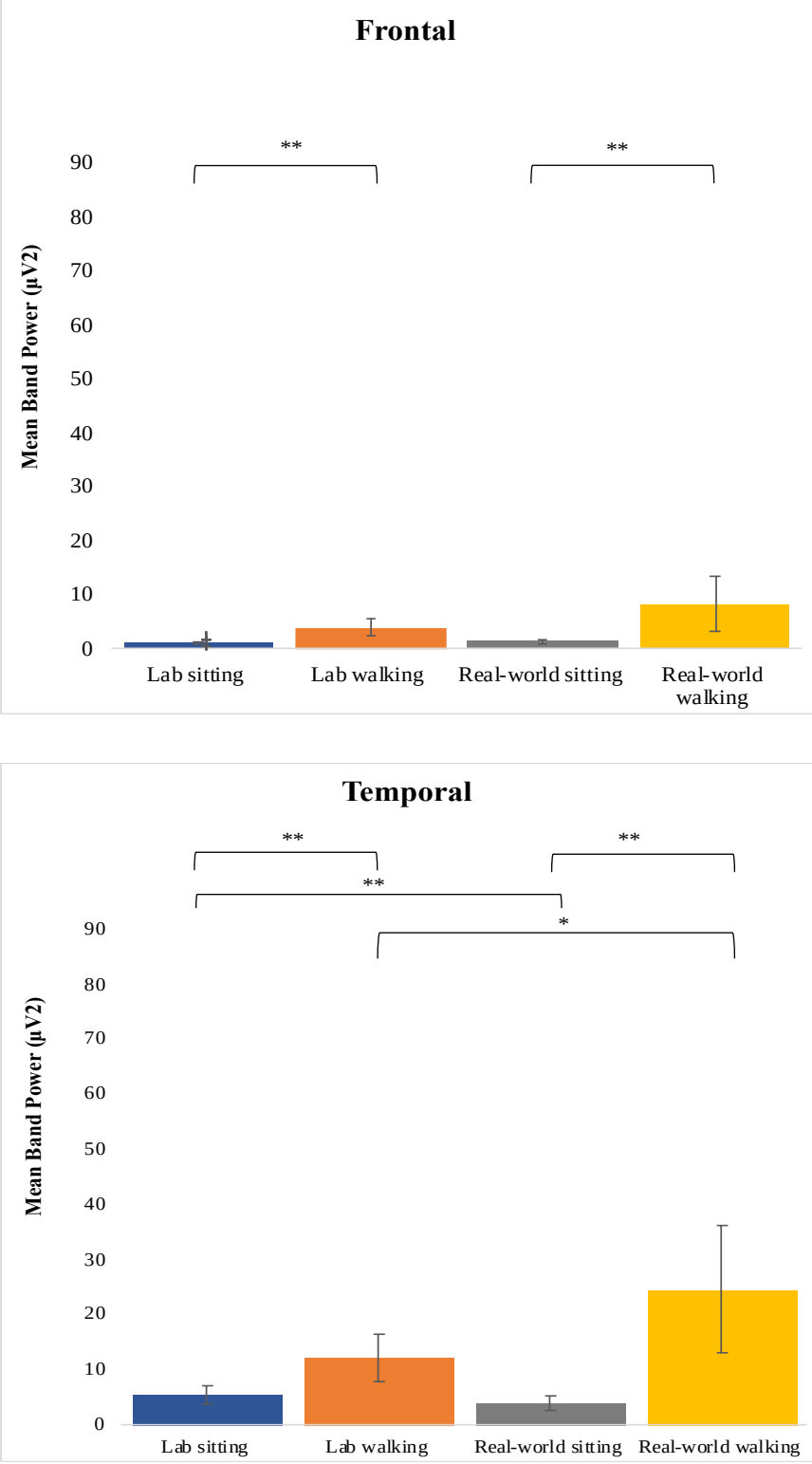
* The mean difference is significant at the .05 level.
- Within-subjects repeated measures ANOVA results non-significant. Simple main effects not analyzed.

3.2.1 Theta

Our results for theta power are presented graphically in **Figure 2**. Theta power in the frontal electrodes was higher in the real-world environment compared to the laboratory, as evidenced by a main effect of environment, $F(1,16) = 6.615$, $p = .020$. No main effect of environment was observed on theta power in the temporal electrodes. A main effect of mobility was found, where theta power was higher during walking compared to sitting in both the frontal and temporal electrodes, $F(1,16) = 56.429$, $p \leq .001$ and $F(1,16) = 90.565$, $p \leq .001$, respectively. An interaction effect of environment and mobility was observed on theta power in the temporal electrodes, $F(1,16) = 16.098$, $p = .001$, but not the frontal electrodes.

Simple main effects revealed higher frontal theta power for walking compared to sitting in both the laboratory ($p \leq .001$) and real-world ($p \leq .001$) environments. Higher theta power during walking was also observed in the temporal electrodes for the laboratory ($p = .001$) and real-world ($p \leq .001$) environments. Significant differences in frontal theta power were not found for sitting or walking across the laboratory and real-world environments.

Figure 2. Theta power graphical results



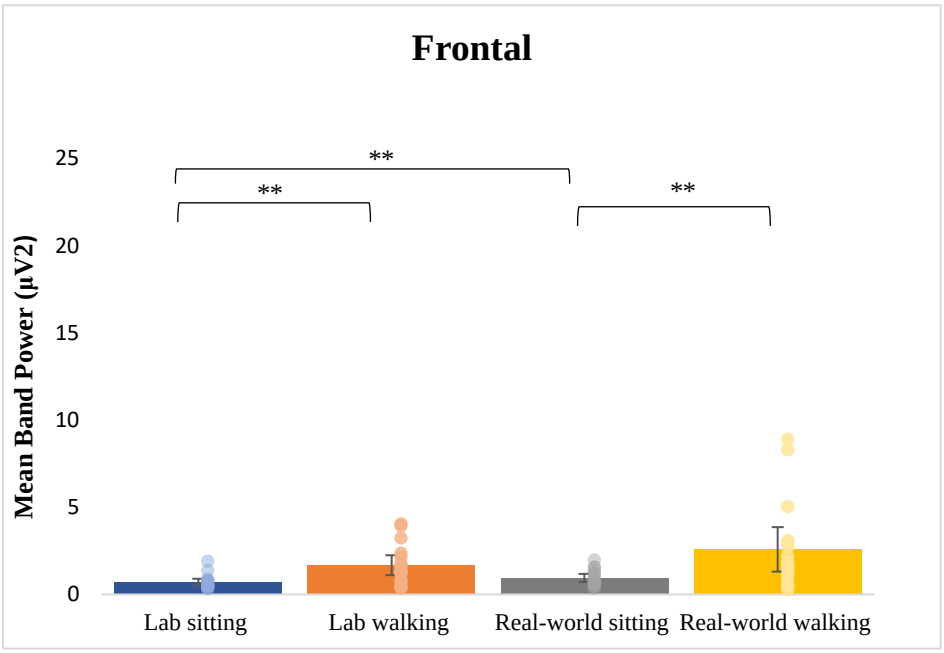
* $p \leq .05$
** $p \leq .01$

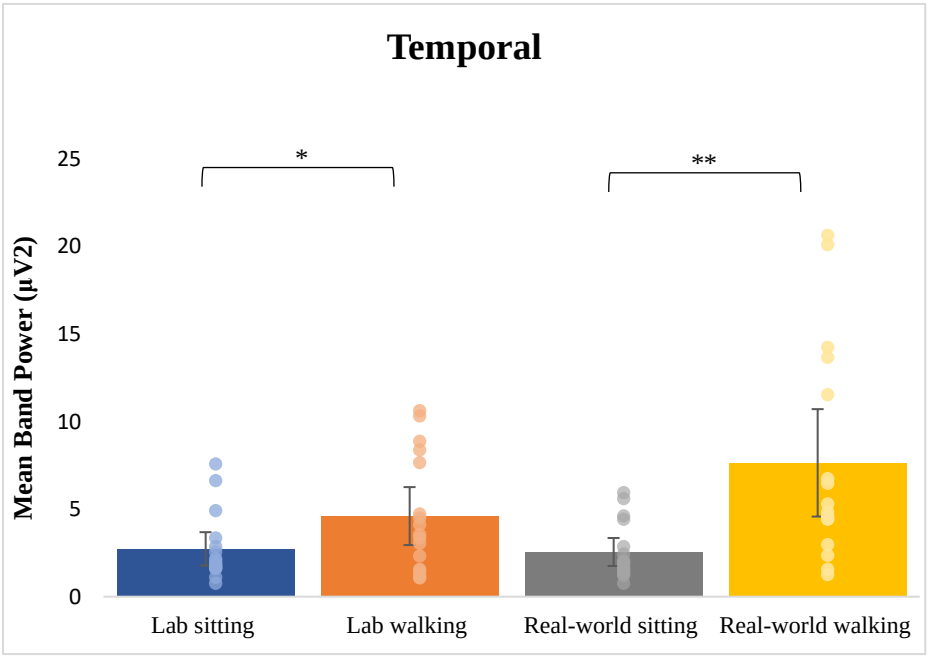
3.2.2 Alpha

Our results for alpha power are presented graphically in **Figure 3.** A main effect of environment on alpha power in the frontal electrodes was observed, $F(1,16) = 7.070$, $p = .017$, where alpha power was higher in the real-world environment compared to the laboratory. No main effect of environment was found on alpha power in the temporal electrodes. Alpha power in the frontal and temporal electrodes was higher during walking compared to sitting, as exhibited by a main effect of mobility, $F(1,16) = 32.786$, $p \leq .001$ and $F(1,16) = 25.841$, $p \leq .001$, respectively. An interaction effect of environment and mobility was observed on alpha power in the temporal electrodes, $F(1,16) = 5.817$, $p = .028$, but not the frontal electrodes.

Simple main effects revealed higher frontal alpha power for walking compared to sitting in both the laboratory ($p \leq .001$) and real-world ($p = .007$) environments. Alpha power was also higher during walking compared to sitting in the temporal electrodes in the laboratory ($p = .016$) and real-world ($p \leq .001$) environments. Higher alpha power was observed while sitting in the real-world environment compared to sitting in the laboratory in the frontal electrodes ($p = .001$). Differences in frontal alpha power were not observed for walking across the laboratory and real-world environments.

Figure 3. Alpha power graphical results





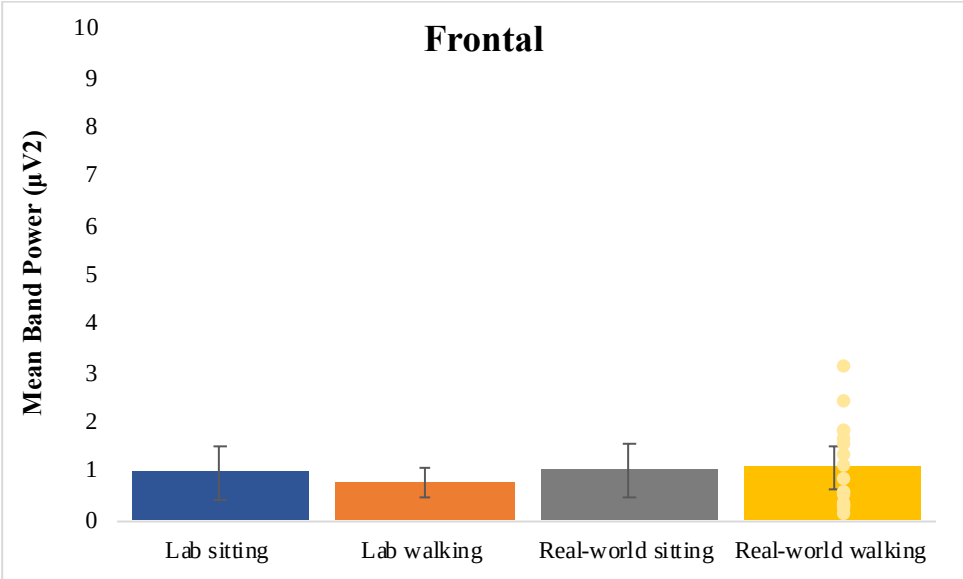
* $p \leq .05$
** $p \leq .01$

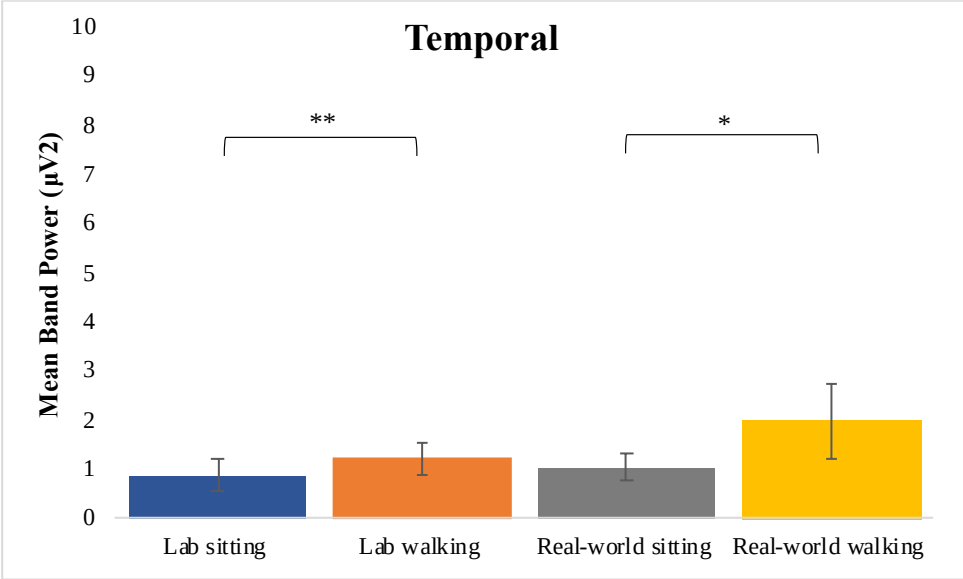
3.2.3 Beta

Our results for beta power are presented graphically in **Figure 4.** Beta power was higher in the real-world environment compared to the laboratory, as shown by a main effect of environment in both the frontal and temporal electrodes, $F(1,16) = 5.909$, $p = .027$ and $F(1,16) = 5.359$, $p = .034$, respectively. A main effect of mobility was found on beta power in the temporal electrodes, $F(1,16) = 12.491$, $p = .003$, where higher power was observed during walking compared to sitting. No main effect of mobility on beta power was found in the frontal electrodes. Interaction effects on beta power were not detected for the frontal or temporal electrodes.

Simple main effects revealed higher temporal beta power for walking compared to sitting in both the laboratory ($p = .002$) and real-world ($p = .020$) environments. Significant differences were not observed for any of the beta power comparisons in the frontal electrodes. Similarly, differences in temporal beta power for sitting or walking across the laboratory and real-world environments were not significant.

Figure 4. Beta power graphical results





* $p \leq .05$
** $p \leq .01$

3.3 Mind Wandering Qualitative Data

The following five unique themes were identified across conditions: 1) “physical sensations and bodily awareness”, 2) “responsibilities and planning”, 3) “environmental awareness”, 4) “mobility”, and 5) “spotlight effect”.

The sections to follow detail the themes identified for each condition.

3.3.1 Laboratory Environment

Three overarching themes were identified for the laboratory sitting condition. The three themes were 1) “physical sensations and bodily awareness”, 2) “responsibilities and planning”, and 3) “environmental awareness”. First, participants frequently noted thinking about their hunger and fatigue. Some participants described thinking about the feeling of their heartbeat and breathing. For the second theme, participants often detailed their thoughts about responsibilities and planning for the day or near future. Most responsibilities and planning were related to academic work and meeting deadlines. However, some participants did mention planning to go to the gym, spend time with family/friends, and cleaning their home. For the third theme, some participants discussed thinking about the environment around them, including the treadmill and curtains directly in front of them, the smell of the room (new fitness equipment), and the bright lights.

Two main themes were identified for the laboratory walking condition. The first theme was “mobility”, where participants described thinking about their gait, balance, and posture while walking on the treadmill. The second theme identified was “responsibilities and planning”. These thoughts were like what was discussed for the laboratory sitting condition.

3.3.2 Indoor Real-World Environment

Three central themes were identified for the real-world sitting condition. The three themes were 1) “environmental awareness”, 2) “spotlight effect”, and 3) “responsibilities and planning”. For the first theme, participants often noted observing other people in the room and the architecture of the building, including the living plant wall. Both visual and auditory environmental awareness were mentioned by participants. For the second theme,

many participants thought about how others were looking at them while they were sitting off to the side and looking around. For the third theme, the thoughts written by participants were like what was previously described for the laboratory environment conditions.

Four main themes were identified for the real-world walking condition. The four themes were 1) “spotlight effect”, 2) “mobility”, 3) “environmental awareness”, and 4) “responsibilities and planning”. For the first theme, participants frequently mentioned thinking about other people looking at them while they walked. Second, participants discussed thinking about their walking pace and pattern, posture, and muscles engaged during walking. Third, as they walked, participants thought about the environmental surroundings, specifically the architecture and layout of the building. Lastly, participants thought about responsibilities and planning for the day or the near future, which mainly related to academic work and deadlines.

Chapter 4

4 Discussion and Conclusion

4.1 Discussion

This study aimed to examine and compare neural processes among young adults during sitting and walking in a laboratory and indoor real-world environment using mobile EEG. Statistical analysis was performed to determine effects of mobility and environment on brain activity across and within the four conditions. In general, our results demonstrated that both mobility and environment may modulate cortical activity, where we observed greater neural activation for walking compared to sitting and for real-world walking compared to laboratory walking. Findings for each frequency band are discussed in detail below.

4.1.1 Theta

We predicted an effect of mobility on theta power, where an increase during walking would be observed compared to sitting. Our results support this hypothesis. In the frontal and temporal electrodes, we found higher theta power during walking compared to sitting in both the laboratory and real-world environment. This finding coincides with previous literature that suggests theta involvement in sensory and motor processes, as well as the integration of the two (Bland & Oddie, 2001; Karakaş, 2020). In our study, whether walking on the treadmill in the laboratory or in the indoor real-world environment, participants likely utilized their sensory and environmental surroundings to execute safe motor movements to ensure that they were balanced and did not fall. This finding supports the notion that theta frequency bands may be involved in the underlying neural mechanisms that provide motor systems with updated information on movement relative to sensory and environmental input (Bland & Oddie, 2001).

We hypothesized that theta power would increase in the indoor real-world environment compared to the laboratory. In line with our hypothesis, we found greater theta power in the real-world environment compared to the laboratory in the frontal electrodes. Previous literature has supported a clear link between theta brain waves and visuo-spatial attention,

navigation, learning, and memory (Herweg et al., 2020; Karakaş, 2020). Therefore, it is likely that the real-world environment required participants to navigate and learn their surroundings as well as pay attention to external stimuli. Our qualitative results do support that participants were actively attending to stimuli in the surrounding environment, which further confirms our interpretation. A central theme from the real-world conditions was “environmental awareness”, where participants frequently noted thinking about visual and auditory stimuli in the environment around them.

4.1.2 Alpha

We hypothesized that alpha power would decrease during walking compared to sitting but were unclear about whether there would be a difference in alpha power between the laboratory and real-world environment. In opposition to our mobility prediction, we found higher frontal and temporal alpha power for walking compared to sitting in both the laboratory and real-world environment. Although our observation of increased alpha power during walking disagrees with findings from some studies (e.g., Cao et al., 2020), our results may be explained by cognitive and attentional control required for walking execution (Cevallos et al., 2015; Sadaghiani et al., 2012). Sadaghiani and colleagues (2012) alluded to a “windshield wiper” metaphor, where alpha produces a pulsed inhibitory effect that is thought to be involved in the clearance and updating of information. Thus, we may have observed an increase in alpha power because participants were utilizing cognitive resources to update incoming information as they walked.

Regarding environmental effects, we found greater frontal alpha power during sitting in the real-world compared to sitting in the laboratory. This finding may be explained by the strong evidence to support increased alpha waves when actively inhibiting processing of visual stimuli (Clayton et al., 2018). Our qualitative results may help to interpret this finding, where participants noted observing other people in the real-world environment and perceived that others may be looking at them. This likely caused some kind of discomfort to participants, which may have resulted in them actively avoiding looking at others in the real-world environment while sitting to ease feelings of discomfort.

4.1.3 Beta

Our results revealed an effect of mobility, where beta power was higher during walking compared to sitting in the temporal electrodes. Initially, we did not form a hypothesis about whether beta power would differ across sitting and walking conditions due to variability in prior findings on beta activity during walking. Previous work has suggested that increases in beta frequency may be observed during movement preparation and after movement execution/resetting, but not during actual movement execution (Barone & Rossiter, 2021; Kilavik et al., 2013; Mustile et al., 2021; Spitzer & Haegens, 2017). Therefore, it is possible that our finding of increased beta power during walking may be explained by the planning and resetting of motor movements that the act of walking requires.

We predicted that beta power would increase in the real-world environment compared to the laboratory. Our results for the frontal and temporal electrodes support this hypothesis. In the absence of a specific task or stimulus, we know that beta frequency is often present when one is actively thinking and alert (Kumar & Bhuvaneswari, 2012), but with the imposition of a specific task, beta waves are prominent in tasks of visual perception, decision making, and working memory, for example (Spitzer & Haegens, 2017). In the real-world walking conditions, beta power may have increased due to greater amounts of environmental stimuli that caught the attention of participants. A central theme from our qualitative data was “environmental awareness”, where participants noted thinking about the layout of the building and the architecture, for example. Another theme identified for the real-world conditions was “spotlight effect”, as participants often detailed thinking about other people looking at them. As described prior, this may have invoked at least to some extent some level of discomfort and alertness among participants in the real-world environment if they felt that others were looking at them.

4.1.4 Impact of Motion on EEG Data

Mobile EEG is a relatively new neuroimaging technique that has been used sparingly in movement-related research. This study is one of few to showcase the potential use of this technology in research involving walking, particularly in a real-world environment. It is

known that EEG may be subject to noise from natural human movement and processes. However, we are confident that the results presented here are a true reflection of EEG signal, and not motion artifacts. Our rationale for this is detailed below.

As preventing artifacts in the first place is ideal, when possible, we instructed each participant to face forward while walking at a comfortable and leisurely pace that would not cause exhaustion or excessive sweating. This instruction was to ensure that participants kept their head straight to limit head movement artifacts, and that they did not walk too fast. Previous literature has suggested that greater precaution for motion EEG artifacts should be taken at higher walking speeds (Nathan & Contreras-Vidal, 2016). Therefore, providing this instruction to participants likely reduced head movement and walking speed artifacts in our data.

Despite our attempts to prevent motion artifacts in our sample, some level of movement contamination was expected and accounted for. We collected 10 minutes of data for the walking conditions instead of five minutes as we did for the sitting conditions. This allowed for artifact-ridden segments of data to be rejected in our analysis, while still preserving a useable amount of data where possible. We conducted a thorough analysis approach on an individual participant basis to optimize artifact rejection and the data for each condition were visualized to note any unusual data. We determined that some of the conditions for our participants were unusable due to motion artifacts, which resulted in the exclusion of 16 participants from our statistical analysis (23 excluded overall). This decision to exclude a large portion of our sample in the analysis was to ensure to the best of our abilities that only EEG signal was included in our results.

Lastly, there is evidence in our results to indicate the reflection of true EEG signal rather than motion artifacts. Using our findings for frontal beta power as an example, the mean beta power values were higher for laboratory and real-world sitting compared to laboratory walking and were comparable to real-world walking. If motion artifacts were driving our results, we would have likely observed significantly higher beta power for the walking conditions. Furthermore, our results coincide with previous neuroimaging

literature that demonstrates greater cortical activation during walking overall (see Section 1.2), which further supports that our findings reflect true EEG signal.

4.1.5 Study Advantages

Our study utilized a within-subjects design, which is statistically more powerful than between-subjects designs (Greenwald, 1976). Another advantage of our study is the incorporation of both laboratory and real-world methods to observe more natural participant behaviors; thus, increasing the generalizability of our results (ecological validity). Incorporating controlled laboratory, semi naturalistic, and true real-world methods into neuroscience research has been highlighted as important and beneficial by researchers to answer certain research questions (Janssen et al., 2021; Matusz et al., 2019). Our study also advantages from the collection of both quantitative and qualitative data. Previous studies on neural activity during walking in young adults have primarily collected only quantitative data. By collecting qualitative data after each condition, this allowed us to capture the thoughts, feelings, and emotions of our participant group and consider how this qualitative information may impact our quantitative findings.

4.1.6 Study Limitations and Future Research Directions

General limitations of EEG include its inability to tell us where the signals are coming from in the brain (inverse problem) and register the activity of singular or small groups of neurons. Therefore, we were unable to infer which brain structures and functions were involved in our study results. We suggest that future research with mobile methods incorporate both temporally and spatially sound technologies (e.g., mobile EEG and fNIRS) when possible.

The mobile EEG system that we selected for data collection was chosen because it is accessible, cost-effective, comfortable for participants to wear without imposing on their natural movements and has been validated for use in research (Krigolson et al., 2021). However, one limitation of the device is that it is limited to four electrodes. Less data to work with was a limiting factor, as some of our data were excluded due to high artifacts. This contributed to the removal of 23 participants from our analysis. Future research with

walking and other movement should account for data loss and collect more data (e.g., more trials, longer recording duration, more points of data collection).

Although including real-world methods was beneficial, it also has limitations that should be acknowledged. In the real-world environment, we were not able to control for all environmental variables (e.g., number of people, noise etc.). Thus, the environment may have been inconsistent across participants and influenced the data that we collected. Likewise, we did not control for participants' walking speed or the time of day that the study sessions were conducted. However, we believe that the advantages of incorporating real-world methods without controlling certain variables outweigh the limitations because this represents the diverse experiences we encounter in everyday life and increases the ecological validity of our findings.

We acknowledge that our sample was composed of educated younger adults with high self-reported stress and anxiety. Since our participants were students, it is possible that some participants were familiar with the real-world environment that we immersed them in. Therefore, our findings may not be reflective of the younger adult population at large who are not university students at Western University. Furthermore, we did not perform statistical analyses with participant characteristics as covariates (e.g., sex, age, DASS-21 scores) due to time constraints. Future research should consider including a more diverse range of participants in terms of education level, income, age, and clinical status. It would also be beneficial for future work to examine covariates statistically to determine any possible relations to neural processes.

4.1.7 Next Steps

The next phase of this study is currently underway. We are expanding our methods to include older adults with and without a history of falls and older adults diagnosed with Parkinson's disease. Our aim is to examine and compare cortical processing during sitting and walking in the laboratory and indoor real-world environment across populations to observe any differences relating to age, cognition, or mobility impairment, for example.

4.2 Conclusion

This study expands the literature on cortical activity during walking in young adults and provides evidence that mobility and environment may modulate neural processing. In general, our findings demonstrate greater neural activity during walking compared to sitting and during walking in an indoor real-world environment compared to a standard laboratory environment. We highlight that supplementing standard research techniques with real-world methods may allow for further insight into neurocognitive processing in everyday scenarios. Future research should consider examining and comparing brain activity from different populations during mobility in laboratory and real-world environments with both temporally and spatially sound neuroimaging technologies.

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Appendices

Appendix A: Ethics Approval Form

Western Research

Date: 21 April 2023

To: Dr. Lindsay Nagamatsu

Project ID: 120364

Study Title: Examining electrical brain activity using mobile electroencephalography in younger adults, older adults, and Parkinson's disease during mobility in a real-world environment

Application Type: Continuing Ethics Review (CER) Form

Review Type: Delegated

Date Approval Issued: 21/Apr/2023 13:32

REB Approval Expiry Date: 13/May/2024

Dear Dr. Lindsay Nagamatsu,

The Western University Non-Medical Research Ethics Board has reviewed this application. This study, including all currently approved documents, has been re-approved until the expiry date noted above.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Please do not hesitate to contact us if you have any questions.

Sincerely,

The Office of Human Research Ethics

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix B: Study Documents and Questionnaires

B. 1 Recruitment Poster

B. 2 Letter of Information and Consent Form

Letter of Information and Consent

Project Title: Mobile Electroencephalography (EEG) and Mobility

Principal Investigator:	**MSc Student:**
Dr. Lindsay Nagamatsu (School of Kinesiology, Western University)	Samantha Marshall (School of Kinesiology, Western University)

Funder: Natural Sciences and Engineering Research Council of Canada (NSERC)

Invitation to Participate: You are being invited to participate in this research study about the underlying brain mechanisms that are responsible for cognitive processing and mobility in younger adults.

Introduction: Cognitive resources, such as attention, are required for safe mobility and navigation through the environment. Previous work looking at cognition and mobility were limited to laboratory settings where participants were stationary, which does not necessarily translate to what would occur in the real-world.

Novel mobile neuroimaging techniques have made it possible to observe brain activity while participants are in motion. Therefore, the present study will examine brain activity in young adults and compare this activity when they are in laboratory and naturalistic settings. This research has the potential to expand our understanding of cognitive processes involved in human mobility in the real world.

Procedure: If you agree to participate, you will be asked to complete one session in the Exercise, Mobility, and Brain Health laboratory (located in Thames Hall) that will be scheduled at your convenience. The total time commitment is ~1.5 hours.

On the day of testing, and before arriving at the laboratory, you will be required to complete the “COVID Self-Assessment” questionnaire (https://www.uwo.ca/coronavirus/self-assessment.html).

When you arrive at the laboratory, you will undergo the formal consent process and will have opportunities to ask questions. After consent is obtained, you will

be invited to complete the demographic questionnaire and anxiety, depression, and stress scale (DASS-21).

You will then be fitted with a mobile EEG headband (Muse brain sensing headband). The headband will be expanded to the largest size and the rubber sensors will be placed behind your ears. Participants with long hair will be asked to pull their hair back in a ponytail or clip to minimize interference. The headband will be tightened to ensure a snug fit against your skin. The headband will then be calibrated to ensure that the sensors maintain a good signal quality throughout the session. After calibration is achieved, you will be doing a series of sitting and walking conditions in random order (10 minutes for each condition). This may include sitting indoors and outdoors, walking indoors (on a treadmill and/or around Thames Hall), and walking outdoors around campus, depending on weather conditions.

Condition 1: Laboratory setting (seated)

In this condition, you will be seated in the laboratory, and we will collect EEG data while you sit awake in a comfortable position.

Condition 2: Laboratory setting (walking)

In this condition, you will walk on a treadmill inside while we collect EEG data.

Condition 3: Real-world setting (seated)

Similar to condition 1, you will be in a seated position and EEG data will be recorded while you sit awake. However, you will be seated outside the laboratory (indoors in Thames Hall or outdoors).

Condition 4: Real-world setting (walking)

In this condition, you will either be indoors in Thames Hall or led outside the laboratory building. EEG data will be recorded while you walk along a pre-determined route.

After each condition, you will be asked to answer an open-ended question about what you were thinking about during the task.

Brain activity during the study will be recorded through the mobile EEG headband and collected by the Mind Monitor app. Created by James Clutterbuck, Mind Monitor displays real-time EEG brainwave graphs. Mind Monitor is exclusively for use with "Muse: The Brain-Sensing Headband" and is "Not an Official Muse app". Please see the full Mind Monitor privacy policy for more information: https://mind-monitor.com/PrivacyPolicy.php

No sensitive information will be inputted into Muse or Mind Monitor.

Inclusion Criteria: 1) Western student aged 18-30; 2) have normal or corrected-to-normal visual and auditory acuity; 3) can walk independently; 4) are right-handed; 5) can read and write in English; 6) have no history of neurological impairment, neuropsychiatric disorder, or eye injury.

Exclusion Criteria: 1) currently are taking psychotropic medication; 2) have a medical condition or other limitation that prevents from walking unassisted.

Risks and Benefits: There are no anticipated risks or discomforts associated with participating in this study. However, it is important to note that no method of internet transmission or storage is 100% reliable and secure.

You may not directly benefit from participating in the study but information gathered may provide benefits to society, which include furthering our understanding the underlying neural mechanisms responsible for cognition and mobility.

Withdrawing: You have the right to withdraw from the study at any point without consequences. If you decide to withdraw from the study, the information that was collected prior to you leaving the study will still be used to answer the research questions. You have the right to have all of your data removed/deleted from the study upon request up until the data is analyzed. No new information will be collected without your permission.

Confidentiality: Your personal information will remain private and confidential. Only the Principal Investigator and research personnel will have access to the data. We will not share your data with anyone outside the study unless required by law. Representatives of The University of Western Ontario Non-Medical Research Ethics Board may require access to your study-related records to monitor the conduct of the research. While we do our best to protect your information, there is no guarantee that we will be able to do so. We will keep any personal information about you in a secure and confidential location for a minimum of 7 years. A list linking your study number with your name, email, and draw entries will be kept by the researcher in a secure place, separate from your study file. If the results of the study are published, your name will not be used.

Compensation: In appreciation for your time, you will have the option to be entered in a draw for a chance to win one of two $25 Amazon gift cards.

Rights of Participants: Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you choose not to participate or to leave the study at any time, it will have no consequences for you or your academic standing.

We will give you new information that is learned during the study that might affect your decision to stay in the study. You do not waive any legal right by signing this consent form.

Questions? If you have any questions about this research study, please contact Dr. Lindsay Nagamatsu OR Samantha Marshall.

If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Research Ethics.

Consent Form

Project Title: Mobile EEG and Mobility

Document Title: Letter of Information and Consent

Principal Investigator: Dr. Lindsay Nagamatsu

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

_____

Print Name of Participant Signature Date (DD-MM-YYYY)

_____

Print Name of Researcher Signature Date (DD-MM-YYYY)

☐ Please check this box if you would like to be entered into the draw.

Email: _____

B.3 Demographic Questionnaire

Mobile EEG and Mobility - Demographic Questionnaire

1. What is your e-mail address (for contact purposes if you win gift card draw)?

   _____

2. How old are you?

   _____

3. What is your biological sex?
   - Male
   - Female
   - Prefer not to respond

4. What gender do you most identify?
   - Man
   - Woman
   - Transgender
   - Two spirit
   - Non-binary/non-conforming
   - None of the above. I identify as:
   - Prefer not to respond

B.4 Depression Anxiety and Stress Scale 21 (DASS-21)

DASS21

Name: Date:

Please read each statement and circle a number 0, 1, 2 or 3 which indicates how much the statement applied to you **over the past week**. There are no right or wrong answers. Do not spend too much time on any statement.

The rating scale is as follows:

0 Did not apply to me at all
1 Applied to me to some degree, or some of the time
2 Applied to me to a considerable degree or a good part of time
3 Applied to me very much or most of the time

1 (s)	I found it hard to wind down	0	1	2	3
2 (a)	I was aware of dryness of my mouth	0	1	2	3
3 (d)	I couldn't seem to experience any positive feeling at all	0	1	2	3
4 (a)	I experienced breathing difficulty (e.g. excessively rapid breathing, breathlessness in the absence of physical exertion)	0	1	2	3
5 (d)	I found it difficult to work up the initiative to do things	0	1	2	3
6 (s)	I tended to over-react to situations	0	1	2	3
7 (a)	I experienced trembling (e.g. in the hands)	0	1	2	3
8 (s)	I felt that I was using a lot of nervous energy	0	1	2	3
9 (a)	I was worried about situations in which I might panic and make a fool of myself	0	1	2	3
10 (d)	I felt that I had nothing to look forward to	0	1	2	3
11 (s)	I found myself getting agitated	0	1	2	3
12 (s)	I found it difficult to relax	0	1	2	3
13 (d)	I felt down-hearted and blue	0	1	2	3
14 (s)	I was intolerant of anything that kept me from getting on with what I was doing	0	1	2	3
15 (a)	I felt I was close to panic	0	1	2	3
16 (d)	I was unable to become enthusiastic about anything	0	1	2	3
17 (d)	I felt I wasn't worth much as a person	0	1	2	3
18 (s)	I felt that I was rather touchy	0	1	2	3
19 (a)	I was aware of the action of my heart in the absence of physical exertion (e.g. sense of heart rate increase, heart missing a beat)	0	1	2	3
20 (a)	I felt scared without any good reason	0	1	2	3
21 (d)	I felt that life was meaningless	0	1	2	3

B.5 Mind Wandering Questionnaire

Please take a few minutes to write down what you were thinking about during the task.

Curriculum Vitae

Name:	Samantha Marshall
Post-secondary Education and Degrees:	Western University London, Ontario, Canada 2021-2023 M.Sc. in Kinesiology, Integrative Biosciences
	University of Waterloo Waterloo, Ontario, Canada 2015-2020 B.Sc. in Honors Health Studies, Co-operative Program
Honors and Awards:	Ontario Graduate Scholarship $15,000, 2022-2023 (declined), 2023-2024
	Canadian Association on Gerontology conference travel grant $250, 2023
	Canada Graduate Scholarship (NSERC) $17,500, 2022-2023
	Mitacs Accelerate Fellowship $25,000, 2022-2023
	University of Waterloo Dean's List Distinction 2016-2020
	University of Waterloo President's Scholarship $2,000, 2015
Related Work Experience	Teaching Assistant Western University 2021-Present
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	Research Assistant Aging and Innovation Research Program, University of Waterloo 2020-2023

Published Journal Articles:

Marshall, S., Gabiazon, R., Persaud, P., & Nagamatsu, L. S. (2023). What do functional neuroimaging studies tell us about the association between falls and cognition in older adults? A systematic review. Ageing Research Reviews. doi: 10.1016/j.arr.2023.101859

Miguel-Cruz, A., **Marshall, S**., Daum, C., Perez, H., Hirdes, J., & Liu, L. (2022). Data silos undermine efforts to characterize, predict and mitigate missing incidents among persons with dementia. Healthcare Management Forum.
doi: 10.1177/08404704221106156

Perez, H., Neubauer, N., **Marshall, S**., Philip, S., Miguel-Cruz, A., & Liu, L. (2022). Barriers and benefits of information communication technologies used by health care aides. Applied Clinical Informatics, 13(1), 270-286. doi: 10.1055/s-0042-1743238

Oral[a] and Poster[b] Presentations:

"Mobile neuroimaging in the real-world: how do brain waves during mobility differ between young adults, older adults with and without a history of falls, and adults diagnosed with Parkinson's disease?", Canadian Association on Gerontology Conference, to be presented October 2023[b]

"Brain Activity in a Real-World Environment", Retiring Minds, Western University, 2023[a]

"Using Mobile EEG during Mobility in a Real-World Environment", Cognitive Neuroscience Society Conference, 2023[b]

"Mobile Neuroimaging and Mobility in Parkinson's Disease", Parkinson Society of Southwestern Ontario Fall Conference, 2022[b]

"Mental Health in Older Adults with a Recent History of Falls", Canadian Association on Gerontology Conference, 2022[b]