Prefrontal Cortical Activation in Naturalistic Walking

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Recommended Citation
Klaschus, Aimee L., "Prefrontal Cortical Activation in Naturalistic Walking" (2020). Honors Undergraduate Theses. 726.
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PREFRONTAL CORTICAL ACTIVATION IN NATURALISTIC WALKING

by

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A thesis submitted in partial fulfillment of the requirements for the Honors in the Major Program in Psychology in the College of the Sciences and in the Burnett Honors College at the University of Central Florida Orlando, Florida

Spring Term 2020
Abstract

Tasks and environments that demand greater attention resources result in greater activation of the prefrontal cortex (PFC). To explore this effect in a naturalistic setting, we used functional near-infrared spectroscopy (fNIRS) to record the PFC activation of six undergraduate participants while they walked in a busy environment (attention-demanding) and quiet environment (non-attention-demanding). Walking speed was recorded as a behavioral correlate. Results indicated that there was no statistically significant difference in walking speed or cortical activity between busy and quiet conditions, though the trend was in favor of the hypotheses. This is likely because crowd density within each condition was not sufficiently consistent between participants and because the sample size was very small. Future study should anticipate data collection constraints by allowing more time for both individual and total data collection in order to collect a sample size with adequate statistical power.
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Introduction

Interacting with a crowded environment may require the use of cognitive resources. Executive control, which is mediated by prefrontal cortex (PFC) structures, is thought to moderate attention by parsing information from awareness based on relevance (Sanbonmatsu, Strayer, Medeiros-Ward, & Watson, 2013). A crowded atrium, for example, presents a substantial amount of information (e.g. sound, motion, social dynamics) that must be categorized as either relevant or irrelevant to an individual, a task which requires attentional control. This attentional control may also limit the resources available for the control of other tasks, such as gait speed and accuracy, which is explored later in this introduction. Since it is the naturalistic complexity of the environment that we are interested in, it is appropriate to choose a naturalistic design.

Naturalistic vs. Laboratory Studies

Naturalistic studies are unlike laboratory studies in that they take place in a less controlled environment. This is a disadvantage when it comes to drawing causal inferences (correlation does not mean causation), since the factors being investigated cannot, by definition, be precisely isolated and controlled for in a naturalistic environment. However, the phenomena that we as researchers are attempting to investigate is a product of a naturalistic, every day, real-world environment. Laboratory environments may allow for causal inferences, but these inferences are always a product of a controlled environment, which may lead to conclusions that have little or no ecological validity. As our understanding of the complexity of neural activity grows, it may become important that research designs increasingly incorporate naturalistic elements in order to uncover subtleties and interactions that otherwise may be lost in a laboratory environment.
Functional Neuroimaging

In order to investigate the neural activity of a participant, we turn to Functional Near Infrared Spectroscopy (fNIRS), which assesses cognitive activation by recording brain oxygenation. Light-emitting diodes (LEDs) in optodes held to the scalp by a tight cap emit light from 650 to 1000nm. This light passes through the skull and the first layer of the cortex before being picked up by corresponding detectors. Some of this light is absorbed by chromophores, but human tissue is relatively “transparent” in this spectral range (Ferrari & Quaresima, 2012). Hemoglobin, the transport protein that allows red blood cells to carry oxygen, is one such chromophore. A higher concentration of oxygenated hemoglobin results in more light being absorbed. The fNIRS system displays the degree of oxygenation in real-time to researchers based on this principle. The presence of increased oxygenated hemoglobin is interpreted to be the result of more neural resources being used in that area. This is typically referred to as “activation.” Researchers infer cognitive activity based on activation and draw conclusions from there.

Other technologies and techniques are also routinely used to assess neural activity. As a neuroimaging technique, fNIRS is a much less expensive alternative to traditional Functional Magnetic Resonance Imaging (fMRI). Despite its lower signal-to-noise (SNR) ratio, fNIRS correlates highly with fMRI measures (Cui, Bray, Bryant, Glover, & Reiss, 2011), making it a reliable alternative for use in psychophysiological studies. fNIRS is both mobile and less sensitive to movement artefacts than fMRI (Cui et al., 2011), which allows for neuroimaging experiments that would otherwise be impossible, such as full-body motion studies. The ability of fNIRS to be used in a mobile modality is vital to naturalistic studies, since the goal of a naturalistic study is to be as close to real-world activity as possible.
Gait and Cognitive Demand

Previous fNIRS studies have established that gait is influenced by higher-order cognitive controls (Mirelman et al., 2014). Simply put, cognitive demand changes gait. A study of older and young adults demonstrated that walking while talking resulted both in greater PFC activation as well as slower gait speed compared to normal walking; the effects were stronger in older adults than young adults (Holtzer et al., 2011). The effect of age was even greater in another study that involved dual-task conditions (i.e. walking with talking and walking with a visuomotor task). Older participants exhibited greater gait speed reduction and PFC activation in both dual-task conditions when compared to young adults (Beurskens, Helmich, Rein, & Bock, 2014). The results of another study tentatively showed greater PFC activation between slow and fast walking conditions, potentially implying that executive function is involved in maintaining walking speeds greater than participants’ preferred walking speed; however, this effect was small and potentially explained by overlapping cortical regions (Metzger et al., 2017).

Precision stepping, unlike walking, remains a relatively unexplored phenomenon in the fNIRS literature. Precision stepping encompasses any walking task that involves non-normal walking, such as matching steps to marks on a treadmill. One study showed PFC activation prior to initiating a normal walking task, as well as during the first half of a task involving walking on predefined spots on a treadmill (Koenraadt, Roelofsen, Duysens, & Keijsers, 2014). A study involving Positron Emission Tomography (PET) scanning (another neuroimaging technique) showed peak PFC activation in walking conditions that involved adjusting to unpredictable changes in treadmill belt speed (Hinton, Thiel, Soucy, Bouyer, & Paquette, 2019), implying the use of cognitive resources to cope with non-standard walking demands. Reinforcing this conclusion, participants following a “novel adaptive walking path” showed greater step error and
slower gait speed while performing a cognitive task (Ellmers, Cocks, Doumas, Williams, & Young, 2016). Use of cognitive resources, whether by the need for precision stepping or a cognitive task like speaking, seems to decrease the cognitive resources available for locomotion and results in greater error, which is in turn compensated for by reduced gait speed.

Experiment

We are therefore interested if walking within a naturalistic environment that potentially presents a high cognitive demand (i.e. is full of people) will result in greater PFC activation and slower gait speed. We are also interested in exploring if the precision-stepping demands of traversing stairs (a non-standard walking task) will also result in greater PFC activation.

In order to investigate this, we had participants wearing an fNIRS cap walk through a busy (attention-demanding; crowded) or quiet (non-attention-demanding; not crowded) environment as well as perform a precision-stepping control task analogous to traversing stairs. We predicted slower gait speed and greater PFC activation (greater OxyHb concentration) in the busy condition compared to the quiet condition, as well as greater PFC activation during the precision-stepping task.
Methods

Participants
We report data from 6 right-handed female undergraduate participants between the ages of 18 and 23 ($M = 21.17$, $SD = 1.72$) at the University of Central Florida. All participants were free of inner-ear, motor, or lower-limb impairments and had normal or corrected-to-normal vision and depth perception. Informed consent was given from all participants according to the final approval guidelines that the University of Central Florida’s Institutional Review Board provided for the study.

Materials
Neuroimaging data was recorded using a NIRSport 88 fNIRS system by NIRx (NIRx Medical Technologies LLC) and a Microsoft Surface tablet (Microsoft Corporation). Twenty channels were arrayed over the dorsolateral prefrontal cortex and held constant in the cap by spacers. The tablet and fNIRS system were carried in a backpack for the duration of the experimental procedure. A custom-made light-blocking overcap was used during the experimental procedure to prevent ambient light from being recorded by the fNIRS optodes.

Procedure
The experiment used a within-subjects design with two conditions: ‘busy’ and ‘quiet,’ which were defined relative to each other. Prior to setting up the fNIRS system, participants did a practice run through the experimental tasks in order to reduce unnecessary confusion or hesitation during the data recording period. Participants first performed a precision stepping control task, which involved a short (approximately 12 foot) segment of walking while matching their steps to 1x1 squares outlined in masking tape. Participants then walked a circuit from the
third-floor lab down the stairs, across the atrium, up the stairs on the opposite side of the building, and back to the starting point. Each segment of the circuit (down the stairs, across the atrium, up the stairs, back) was given a standardized starting time relative to the beginning of recording. A researcher followed behind the participant, recording the times when they finished a segment and instructing them when it was appropriate to begin the next. A second researcher recorded the participants gait speed using standardized markers on the atrium floor, as well as collecting data to quantify the degree of business/quietness in the atrium by taking a photo from a standardized location. In each picture, people within defined areas of the atrium were counted and reported as crowd density. Participants walked the circuit twice for each condition (i.e. twice in the busy condition, twice in the quiet condition). The busy condition was anticipated to be 20 minutes before class began in the Psychology auditorium, when students were congregated and waiting for the previous class to get out. The quiet condition was anticipated to be 15 to 20 minutes after this, when the congregated students had gone into the auditorium and the previous class had departed the Psychology building.
Analysis

fNIRS

Data processing was done using nirsLAB (version 2019.04, NIRx Medical Technologies, LLC, Brooklyn, NY, USA). Behavioral trigger markers were added manually to each data file based on splits recorded on researcher stopwatches during data recording. At the beginning of pre-processing, spike artifacts and discontinuities were detected and eliminated automatically in nirsLAB. Any change between adjacent data points larger than five standard deviations from the mean for each channel’s time course was considered an artifact. Data were then bandpass-filtered to remove slow data drift (low cutoff frequency = .01Hz) and high frequency noise (high cutoff frequency = .2Hz).

Following preprocessing, raw optical density values were transformed to produce estimates of oxygenated hemoglobin (oxy-Hb) concentration changes at each sample point using the modified Beer-Lambert Law in nirsLAB. Hemodynamic state conversion parameters were based on Gratzer and Kollias (2009). In nirsLAB, we performed the standard and widely-used method of general linear model-based data analysis that uses statistical parametric mapping (SPM; e.g. Tian & Liu, 2014). For level 1 (individual participant) analysis, six regressors were included in the model to measure the influence of each task in the walking circuit (walking from the start, stairs down, pre-atrium pause, atrium walk, stairs up, walking back to start) for a total of six regressors plus an intercept coefficient. Serial correlation was removed by precoloring with a Gaussian kernel (FWHM = 4s). Group analysis (SPM level 2) was carried out on Beta values estimated during level 1 modeling. The SPM level 1 and 2 sequence constitutes a random effects model analysis (Mumford & Poldrack, 2007).
Results
An alpha level of .05 was used for all of the following statistical tests.

Behavioral
We expected a reduction in gait speed between conditions, predicated particularly on the results reported by Holtzer et al. (2011). A paired samples t-test of the crowd density (measured in total people within a defined portion of the atrium with an area of about 8,000 square feet) between the busy ($M = 14.83$, $SD = 9.15$) and quiet ($M = 8.83$, $SD = 4.83$) conditions did show a significant difference ($t(5) = -2.24$, $p = .04$), indicating that participants did experience a more crowded environment in the busy condition.

Walking time, quantified as the time in seconds it took participants to cross a marked section of the atrium approximately 70 feet across, did not change significantly between conditions ($t(5) = -1.53$, $p > 0.05$), with a slightly slower mean walking time in the busy condition ($M = 15.55$, $SD = 1.13$) than in the quiet condition ($M = 14.81$, $SD = 1.43$).

Neuroimaging
An analysis of variance (ANOVA) was conducted on the regression coefficients of all channels (1-20) to see if there were any statistically significant differences in mean OxyHb concentration during the atrium walk in the busy condition, the quiet condition, and the precision stepping control. The precision stepping control was included in the analysis under the assumption that the control certainly required the use of cognitive resources in the PFC, as demonstrated by Koenraadt et al. (2014). No significant differences between conditions were observed in any channel, with the closest being channel 8 ($F(2,15) = 3.48$, $p = 0.06$), which is approximately over Broadmann area 46, an area which sustains attention, working memory, and executive control.
Comparing the precision stepping control task using a paired-sample t-test to baseline activation before the task yielded no significant channels, though the channels with greatest activation were 8 ($t(5) = -1.95, p = 0.05$) and 9 ($t(5) = -1.92, p = 0.06$). OxyHb was trending higher in the busy condition ($M = -1.33e-04, SD = 4.58e-04$) than the quiet condition ($M = -1.94e-05, SD = 5.97e-05$).
Discussion

This study was conducted based on the hypothesis that walking within a busy environment would require greater cognitive resources than walking in a comparatively quiet environment, resulting in greater PFC activation and slowed gait speed. The results did not bear these hypotheses out, either in the behavioral measure of walking or in the hemodynamic response. This may be due more to methodology and circumstance than an incorrect hypothesis. However, the results were trending in the anticipated direction, with slower gait speed and greater OxyHb concentration in the busy condition, so the statistically insignificant nature of this trend may also be due to the inadequate statistical power of our limited sample size.

In addition to the issues with sample size, the lack of statistical significance of the behavioral measures may be because, as the literature has shown, the effects of cognitive demand on gait in young adults is less than in older adults (Beurskens et al., 2014; Holtzer et al., 2011). Without a sufficiently extreme difference in the demands of the busy and quiet conditions, the young adult sample may simply not have been affected enough to demonstrate the expected reduction in gait speed.

Channel 8, located over BA46, was consistently the closest to significance in our analyses. This also supports our hypothesis, since BA46 is associated with working memory, sustaining attention, and, executive control of behavior (Kübler, Dixon, & Garavan, 2006). Since these near-significant results also occurred when comparing the precision stepping control to baseline, there is an indication that conscious control of gait may also use similar attentional resources to navigating a crowded environment.
In terms of statistical analysis, it may have been more beneficial to examine the correlation between cognitive activation and crowd density, rather than parsing conditions into busy and quiet relative to one another. This is an issue specifically because there was a large amount of overlap between the crowd densities of the busy and quiet conditions. Some participants had a greater crowd density in their “quiet” condition than other participants had in their “busy” condition. Without a very clean division between the conditions labeled as quiet or busy, an analysis of variance is flawed at best and counter-productive at worst. Correlational analysis is a better choice if future studies experience similar conditions to this one.

Future study should also allow more time for data collection, both in terms of collecting the individual participant data as well as the total span of the data collection period, in order to successfully collect a greater amount of usable data. Sufficient time is necessary to compensate for unusable participant data. Meeting the requirements for a quiet vs. a busy condition proved to be extraordinarily difficult if not completely impossible for a large portion of participants. Most sessions were planned to have the busy condition followed by the quiet condition, given that the density of the crowd in the atrium slowly built until the doors to the auditorium opened, followed by a drastically less dense crowd for the quiet condition. The busy condition in particular was very easy to miss (on one memorable occasion by about a minute). Given constraints on the amount of time participants agreed to volunteer, if the busy condition was missed it was not possible to wait for the atrium crowd to gather again.

In addition, some threshold of relative difference should be used to separate the busy and quiet conditions (e.g. the busy condition has $\geq 2$ times the crowd density of the quiet condition). Alternatively, an absolute number (e.g. 0-15 people for the quiet condition, 15 or greater for the
busy condition) may be equally useful. Other measures of environmental complexity may also be useful in quantifying the differences between conditions, such as a decibel meter.
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