The Feasibility of fNIRS for Gait Research Involving Beat Perception and Synchronization

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Abstract

In music-neuroscience research, the basal ganglia (BG), premotor cortex (PMC), supplementary motor area (SMA) and pre-SMA are crucial for beat perception and maintenance of gait (Chen et al., 2008; Geiser et al., 2012; Grahn & Brett, 2007; Grahn & Rowe, 2009; Kung et al., 2013). Functional magnetic resonance imaging (fMRI) has been able to demonstrate dissociated activation levels in these regions during beat perception tasks between healthy and PD participants (Elsinger et al., 2003; Rahimpour et al., 2022). Furthermore, gait characteristics have been analyzed using a pressure sensitive walkway, allowing researchers to observe how PD patients differ from controls in gait characteristics and the ensuing impact from rhythmic auditory stimulation (RAS) (Ghai et al., 2018; Keloth et al., 2019). Although neuroimaging studies of beat perception and gait research have paved their own respective paths in music-neuroscience research, not until recently has there been any attempt to combine them. Considering the profound mobility limitations with fMRI, functional near-infrared spectroscopy (fNIRS) has made a resurgence to compensate for these restraints (Pinti et al., 2020). fNIRS provides a dynamic method of cerebral cortex imaging which sacrifices spatial resolution to allow for impressive mobility (Herold et al., 2017, 2018; Pinti et al., 2020), giving the potential to record cortical activity during real-life tasks such as, in our case, listening to music and walking. We perform a crude pilot experiment to analyze the potential feasibility of fNIRS in the context of a gait synchronization study using a pressure sensitive walkway. A plethora of limitations are revealed, enabling discussion about potential future studies which could produce proper, interpretable data which is valid and reliable. If such an experiment is deemed feasible, future studies could potentially uncover the neural correlates of gait characteristics displayed on

a pressure sensitive walkway, the gait impairments observed in PD, and the effects of RAS in alleviating said impairments.

Introduction

The Behavioral Implications of Beat Perception in Gait and Parkinson's Disease

When listening to music, a common hallmark of an individual's listening experience resides within their perception of the beat, also understood as the underlying 'pulse' of the music (Nguyen et al., 2018). This perception is also argued to be an innate ability (Winkler et al., 2009), although life experiences can certainly have a continuous impact (Cross, 2001; Gerry et al., 2010; J. R. Iversen et al., 2008; Phillips-Silver & Trainor, 2005). Beat perception represents a singular component to a larger array of temporal perception and production processes important "for normal hearing, speech, motor control, and music" (Nguyen et al., 2018, p.507). One offshoot of these processes is sensorimotor synchronization (SMS): "the coordination of rhythmic movement with an external rhythm" (Repp & Su, 2013, p.403). SMS closely correlates with an individual's beat perception ability, allowing for behavioral studies to focus on the different experimental conditions which could impact a person's beat perception or synchronization ability (Nguyen et al., 2018). However, SMS is importantly distinguished from general beat perception in it being an ability which is developed over time, gradually manifesting itself in the form of, for example, finger or foot tapping, walking, and dancing to the beat (Repp & Su, 2013). To test individual differences in beat perception and subsequently SMS ability, the Beat Alignment Test (BAT) has been implemented frequently (J. Iversen & Patel, 2008). The BAT allows for analysis of not only the effects of different experimental conditions but for how these effects differ between proficient and poor beat perceivers.

Research in healthy individuals focusing on gait characteristics demonstrates these different conditions through changes to groove and familiarity. Increasing the groove, the element which makes one want to move, along with the familiarity of the music, improves stride velocity and consistency (Leow et al., 2014, 2015). High-groove and high familiarity music stimuli are also implicated in participants improving the synchronization of their steps with the music (Leow et al., 2014, 2015). Compared to baseline silent walking, however, a detriment to gait variability is observed during attempts to synchronize steps to the beat (Leow et al., 2018, 2021). Enjoyment has also been discussed as a factor in improving gait characteristics (Leow et al., 2015) although recent findings suggest it is not a determining factor in observable gait behavior changes (Roberts et al., 2021). Moreover, Ready et al. (2019) note that step synchronization may only be beneficial to those who are good beat perceivers, while poor beat perceivers have a detrimental gait response when attempting to synchronize. In sum, these behavioral studies demonstrate that an individual's beat perception ability, in conjunction with groove and familiarity, generate nuance to the context in which gait SMS treatment may be applicable.

In contrast to healthy individuals, gait impairments are consistently observed in neurodegenerative conditions such as Parkinson's Disease (PD) (Blin et al., 1990; Ebersbach et al., 2013; Hausdorff et al., 1998). PD patients struggle to discriminate between rhythms which contain an underlying beat, suggesting impairments in beat perception processes (Grahn & Brett, 2009). Combined, these impairments in PD speak to the necessity of internal timing, rhythmic locomotion, and automaticity for walking in general, but also during dual-task processes involving walking (Nombela et al., 2013). These gait disturbances can become defining factors for an individual with PD as their presence can cause falls, injury, and therefore a reduction in

quality of life (Gray & Hildebrand, 2000; Moore et al., 2007; Wielinski et al., 2005). Fortunately, external auditory cues, most prominently in the form of rhythmic auditory stimulation (RAS), can reduce gait deficits in PD (Ghai et al., 2018) and subsequently the number of falls (Thaut et al., 2019).

The Neuroanatomical Correlates of Beat Perception and Parkinson's Disease

PD is most often characterized by the loss of dopaminergic neurons within the basal ganglia (Brooks et al., 1990). It is important to recognize that this loss leads to reduced dopaminergic innervation to the supplementary motor area (SMA), causing the beat perception, synchronization and gait deficits frequently observed (Cannon & Patel, 2021; Proksch et al., 2020; Rao et al., 1997). Understandably then, the SMA is seen to be a part of a motor cortico-basal-ganglia–thalamo-cortical (mCBGT) circuit thought to be essential for beat perception and motor synchronization processes (Grahn & Rowe, 2009; Merchant et al., 2015; Rao et al., 1997). Functional magnetic resonance imaging (fMRI) has allowed researchers to verify the activity of the SMA during these temporal processes. These regions, which are active within an fMRI of healthy participants, are the same regions displaying abnormal functional activity in fMRI's of PD patients. A recent review by Rahimpour et al. (2022) emphasizes the plethora of literature demonstrating either hypoactivation or hyperactivation within the supplementary motor complex as being a critical determinant of the temporal processing and gait deficits seen in PD.

Within healthy participants, fMRI has revealed prominent activity in motor regions such as the premotor cortex (PMC), SMA, pre-SMA and the basal ganglia during beat perception tasks (Chen et al., 2008; Geiser et al., 2012; Grahn & Brett, 2007; Grahn & Rowe, 2009; Kung et al., 2013). These studies demonstrate the motor cortex activity in the absence of any movement, indicating the importance of the PMC and SMA in beat perception regardless of whether SMS is

present. Indeed, individuals with different beat perception ability reveal different brain activity: strong beat perceivers show greater activity in the SMA and PMC (Grahn & McAuley, 2009; Grahn & Schuit, 2012). Moreover, lesioning studies suggest a role for the SMA in rhythm reproduction (Halsband et al., 1993) while transcranial magnetic stimulation suggests a role for the PMC in auditory-motor synchronization processes (Giovannelli et al., 2014). The contrast between healthy and PD patients during behavioral tests and fMRI have therefore been profound in defining the behavioral and neuroanatomical correlates of temporal processes.

The Desire for Movement: Transitioning from fMRI to fNIRS

fMRI is undoubtedly an incredible functional neuroimaging tool due to its respectable spatial and temporal resolution (Glover, 2011). Although simple tasks with isolated movement to peripheral modalities is possible, the mobility limitations of fMRI become apparent when tasks requiring more global movement are desired. This divergence is seen within temporal processing studies: fMRI permits detailed functional imaging during finger tapping tasks (Witt et al., 2008) while gait analyses and the effects of synchronization remain behavioristic in nature with regional associations being correlated via the impairments observed in PD (Nombela et al., 2013). Many researchers have used fMRI to effectively observe functional activity during gait tasks by asking participants to imagine walking (Hamacher et al., 2015). Although this can give a partial representation for brain activity during locomotion, understandably, there are functional activity distinctions between imagined and real walking (la Fougère et al., 2010).

fNIRS is a neuroimaging methodology comparative to fMRI but which surpasses it most prominently in the realm of locomotion. fNIRS sacrifices spatial resolution to acquire the ability for functional activity recordings during real-life mobile tasks such as walking or exercise (Herold et al., 2018; Koenraadt et al., 2014; Perrey, 2008a). Using near-infrared light, fNIRS can

observe hemodynamic changes in tissue chromophores such as oxygenated and deoxygenated hemoglobin (HbO, HbR) in the cerebral cortex (Ferrari & Quaresima, 2012; Jöbsis, 1977). Unfortunately, the functional activity being seen during a task is only representative of the first two or three centimeters of the cerebral cortex – a key limitation when compared to fMRI's ability to record whole brain activity (Ferrari & Quaresima, 2012). fNIRS is also at the mercy of physiological signal interferences, which, especially during tasks involving movement, can become very prominent in hiding the hemodynamic changes directly related to the variable in focus and can be intensified via the scalp (Erdoğan et al., 2014; Obrig et al., 2000). These factors culminate into the prevailing struggle of the current day on how to process fNIRS data in a manner which can effectively, among other things, tackle the motion and physiological artefacts (Herold et al., 2017, 2018).

	fMRI	fNIRS
Strengths	• Non-invasive • Repeatable • Widely available • Superior spatial resolution • Whole brain measurement (lateral surface and depth)	• Non-invasive • Repeatable • Comparable temporal resolution to fMRI • Inexpensive • Portable • Less restriction on motion
Limitations	• Expensive • Strict restrictions of motion • Need for supine position • Noisy scanner • Physiological noise • Restrictions based on metal in the body • Restrictions based on claustrophobia	• Limited to frontal regions and surface analysis • Physiological noise (including superficial scalp signals) • Lacks anatomical information • Interpretation challenges related to multiple sources of vascular signal

Figure 1: **The Strengths and Limitations of fMRI and fNIRS** (Scarapicchia et al., 2017)

Even with the options of electroencephalography and positron emission tomography, fNIRS is still considered as the most suitable methodology for neuroimaging during walking due to its affordability, safety, excellent temporal resolution and respectable spatial resolution

(Perrey, 2008b). Most gait studies using fNIRS have focused on healthy individuals and PD patients within dual-processing tasks, precision stepping tasks, walking over obstructed or unobstructed paths, and highlighting activity levels within primary and supplementary motor and sensory cortices (Bishnoi et al., 2021; Menant et al., 2020).

Combining Gait Characteristics and fNIRS amidst Rhythmic Stimuli Interventions

Research applying fNIRS within the context of analyzing motor performance during rhythmic interventions is extremely limited. In healthy participants, fNIRS was used during rhythmic short-term training of tapping on an e-drum and the effects of RAS during training were considered. Results indicated that brain activity was reduced in premotor regions when RAS was present during rhythmic training (Curzel et al., 2021). Another group of researchers have proposed a protocol for assessing brain activity in PD patients in response to SMS within a finger tapping paradigm spanning multiple weeks (Pu et al., 2020). However, to the best of our knowledge, this protocol has not been experimentally used. Finally, one study assessed the effects of RAS on gait while young and old participants walked on a treadmill with an accelerometer recording gait data while corresponding brain activity was recorded using fNIRS. Results indicated that RAS increased cortical activity, especially in the prefrontal cortex, and correlated with a decrease in gait variability in older participants (Vitorio et al., 2018). To our knowledge, however, no studies have analyzed the effects of RAS on gait characteristics with fNIRS and a pressure sensitive walkway which can track the different gait characteristics such as stride length, width, and velocity.

This present pilot study considers the possibility of filling this gap in the research by assessing the feasibility of a relatively novel fNIRS device produced by NIRx Medical Technologies: the NIRSport2. Crude fNIRS data is retrieved from a simple paradigm assessing

potential changes in supplementary and primary motor regions between baseline silent walking, free walking with instrumental music, and synchronized walking with instrumental music. We hypothesize that a potentially larger study in the future with a more robust paradigm could be feasible if the predicted and unpredicted limitations identified within the current paradigm and preliminary fNIRS data retrieved here are improved upon.

Methods

Participants

4 participants were used across the entirety of the study, 2 of which completed the online and the in-person session while 1 participant completed only the online survey and 1 participant only the in-person session. The mean age of participants who completed the survey was 26.33 (SD = 3.79), 1 identified as a musician while the other 2 participants who completed the survey did not. Each survey participant identified as a male and was right-hand dominant, the individual who only did the in-person session was a female and their dominant hand was not recorded. No participants claimed to have any hearing loss or any mobility impairments which would impact the in-person portion of the study in any way. Every participant had dark brown or black hair of varying lengths; color was recorded as different darker hair colors have been seen to impact the probing light intensity by 20-50% (Koizumi et al., 1999).

Survey

The online survey contained four sections which covered all necessary information of interest.

The first section contained a letter of information with ethics statements and a letter of general consent. Participants were guided through a more detailed ethics consent form in-person, and which contained more information regarding fNIRS and the gait synchronization task on the pressure sensitive walkway.

The second section focused on identifying which music would be most suitable across the participants participating in the in-person part of the experiment. 10 instrumental clips of popular songs from the last twenty years were played and participants were asked to rate each clip on a scale of 1-10 for their familiarity, desire to dance (referred to as groove) and enjoyment of that particular song. For each song, a single score was recorded – calculated as the mean of the 3 category means. The top 3 songs were therefore considered to be the songs with the highest average familiarity, groove and enjoyment and were used as the three instrumental stimuli for the in-person portion of the study.

The third section contained a beat alignment test (BAT) to analyze each participant's ability to perceive whether beeps, played during a clip of instrumental music, were in alignment with the beat of that particular clip. Three trial runs were included to allow for participants to understand the task and then 16 clips with varying difficulty of beat perception were played. Instructions were specific in asking the participants to not physically tap their finger or foot in attempting to perceive whether the beeps were aligned with the beat.

The fourth section contained basic demographic questions discussed in the ***Participants*** section above.

In-Person Gait and fNIRS Experiment

Participants who committed to the in-person portion of this study arrived in the lab and were guided through the detailed fNIRS and gait ethics consent form. Shoes were removed because the soles were all wet from the snow and winter weather outside at the time with the intention of preventing moisture from getting on the pressure sensor walkway. As the 16-foot pressure sensitive walkway (see Appendix A**),** fNIRS cap, optodes, accelerometer and Aurora programming was set up (see Appendix B), participants were explained the basic structure of the

experimental paradigm. Specific instructions were given on where to walk on the mat and how to make large turns when turning around to avoid pivoting and maintain their stride. Black tape indicated the locations on each side of the pressure sensor walkway as to how far they should walk before turning around. Firstly, participants walked up and down the gait mat in silence for 120 seconds so that baseline motor cortex activity could be understood without the effect of music. Once the gait mat was re-configured, participants then synchronized their walking on the gait mat for another 120 seconds while the instrumental music selected from the survey results was played. After a 30 second rest, participants then freely walked on the gait mat to the same instrumental song for another 120 seconds. This was repeated for each of the 3 songs with the baseline walking only being done once at the beginning of testing. Throughout the entire experiment, participants were asked about how they felt with the fNIRS cap and small backpack used to carry the NIRSport 2 device. The backpack was adjustable enough to accommodate different heights, weights and broadness of shoulders or chest.

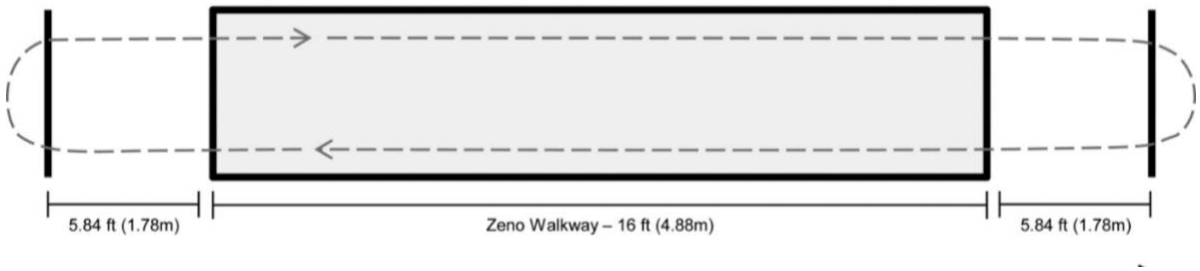

Figure 2: **Pressure Sensitive Walkway Layout**

Participants walked in manner as displayed by dashed arrows and turned in large U-turn like fashion to avoid pivoting. Trials were determined based on the 120 second length of the instrumental clips of music, not on the number of walks up and down the mat. Note: See Ready et al. (2019) for original figure.

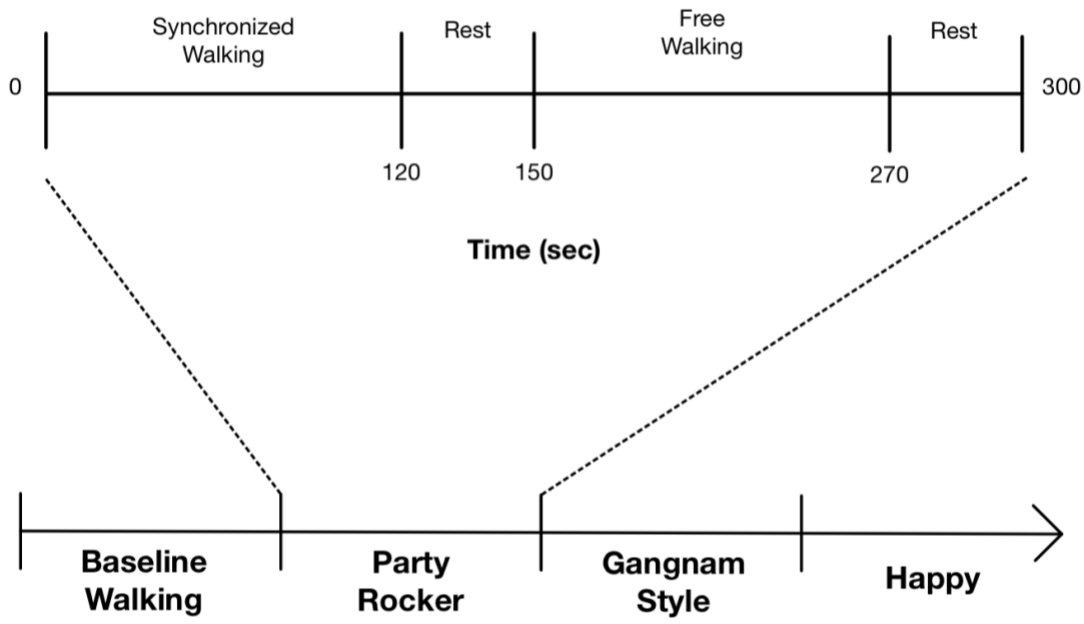

***Figure 3*: Experimental Paradigm**

Each participant began with 120 seconds of baseline walking. This was succeeded by 3 sequential experimental trials, each using a different piece of music. Participants synchronized to the piece of instrumental music for 120 seconds, rested for 30 seconds in silence, free walked with the music playing and then rested again. The time between each music trial was not concrete and related to the time it took to reset the gait mat and Psychopy program. Each piece of music was an instrumental version of the original.

Psychopy Paradigm

Psychopy was used to structure the experiment with 120 second blocks of free walking and synchronization while simultaneously playing out loud the selected instrumental music. This paradigm consisted of an initial testing phase to ensure a connection with the Aurora and Lab Streaming Layer (LSL) program allowing for automatic triggers to identify the time point where free walking and/or synchronization tasks began throughout data collection. This was followed by the 120 second block of baseline walking which then led into the first 120 seconds of synchronized walking with music followed by the 120 seconds of free walking with music. A trigger was sent in Aurora when the synchronized and free walking tasks began. Each block came with an audible announcement of “Free walking”, “Rest” and “Synchronized walking” from the laptop allowing for consistent instruction to the participant on which part of the

experiment they were on. For both walking phases, the audible announcement cued the beginning of the instrumental music selected for that respective trial. Once the first full trial was completed with the first song instrumental, the LSL testing phases and silent walking block were removed, the music file was manually changed, and the trial began at “Synchronized walking”. This procedure was repeated for the final piece of music.

Figure 4: Order of Operations:
Load_lsl: Ensure Lab Streaming Layer (LSL) is properly connected to the PsychoPy program for effective triggering.
Wait: Insure fNIRS is recording, record baseline walk
Trial 1: Synchronized walking
Trial 2: Free Walking
Loop: Return to *Trial 1* to perform tasks with the second and third instrumental pieces

fNIRS Data Pre-Processing Pipeline

Event timing correction was implemented to expand upon the triggers marked throughout the paradigm to have clear distinctions between each interval of synchronized walking, rest, and free walking among the 3 trials involving their respective pieces of instrumental music.

Because all the tasks were predominantly motion based, different motion correction methods were implemented in the attempt to control for the motion artefacts which can be produced from physical shifts of the cap causing the optodes to move, hair to be displaced, and light detection to be impacted (Menant et al., 2020). A hybrid approach of spline interpolation and Savitzky-Golay filtering (SplineSG) was most effective in controlling for both baseline shifts in the signal and smoothing the high-frequency spikes (Jahani et al., 2018). SplineSG was succeeded by a wavelet filter (Molavi & Dumont, 2012) to ensure the removal of any remaining motion artefacts. A high-pass filter above 1/60 Hz was also used to remove instrumental artefacts

and certain low-frequency physiological artefacts (Herold et al., 2018; Huppert et al., 2009; Menant et al., 2020).

The data was then converted to HbO and HbR concentrations using the modified Beer-Lambert Law and resampled to a 1 Hz scale. Individual datasets were then run through the 1st level general linear model (GLM) and then combined via 2nd level GLM to observe mean fixed effects. Musical Walking versus Baseline Walking was first displayed on the motor montage where isolated HbO and HbR concentrations could be compared for each individual channel between source and detector. The same was done for Synchronized Walking versus Free Walking comparisons.

Results

Survey and BAT

The complete survey with music familiarity, groove and enjoyment scores, BAT results and anonymized demographic information can be found in Appendix A. When taking the total mean value from the mean familiarity, groove and enjoyment scores based on the ten-point scale, results indicated *Happy* (7.78) as the song with the highest score, *Gangnam Style* (7.22) as the second highest and *Party Rock Anthem* (7.11) as the third highest.

BAT results indicated that Participant 1, who was the self-identified musician, had the highest accuracy (87.5%), Participant 2 had the second highest accuracy (75%) and participant 3 the lowest accuracy (56.25%). Overall, 50% of the BAT questions were answered identically between all 3 participants. Ready et al. (2019) previously identified the good and bad beat perceivers by defining the higher and lower modes as the thresholds: 76% and above were considered good beat perceivers; 58% and below were considered bad. Based one these thresholds, we therefore had one good, one moderate and one bad beat perceiver.

fNIRS Data Analysis

Raw Data

Preliminary raw data analyses displayed the desired increases in activity during the baseline, synchronized and free walking intervals for participants 1 and 2, however, participant 3 displayed more chaotic intervals compared to the two others.

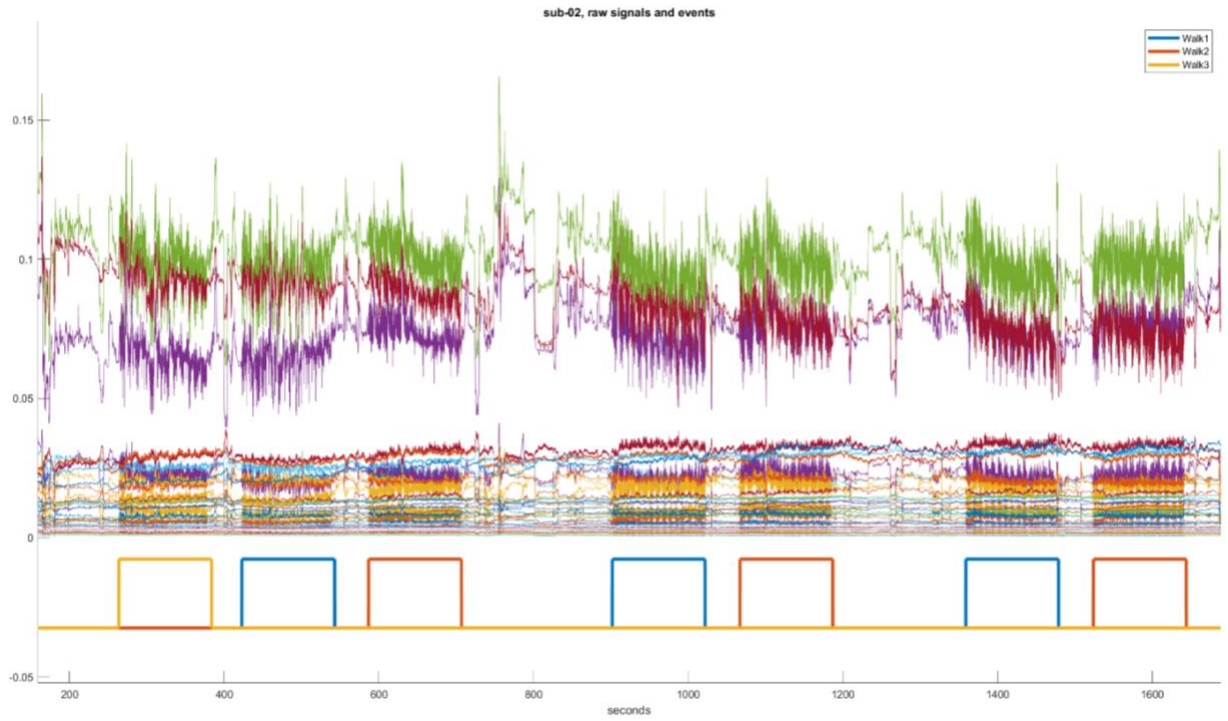

***Figure 5*: Participant 2 Raw Data**

Time corrected raw data for participant 2 shows initial baseline walking interval (Yellow / Walk 3), 3 synchronization intervals for each respective song (Blue / Walk 1) and 3 free walking intervals for each respective song (Red / Walk 2). Each line corresponds to a specific channel each with wavelength recording of either 760 nm or 850 nm. 10 channels on right hemisphere, 10 channels on left hemisphere, 2 wavelengths per channel, therefore 40 signals in total.

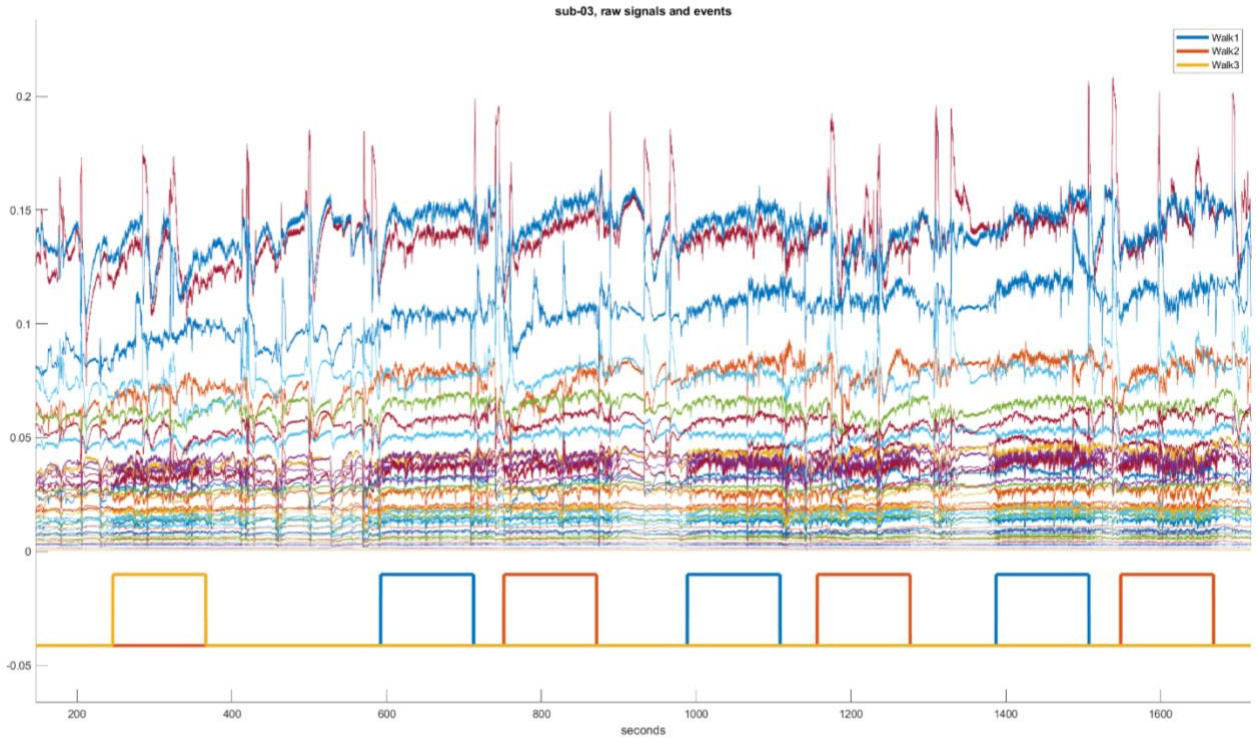

***Figure 6*: Participant 3 Raw Data**

Time corrected data shows much less distinct intervals of raw activity during the allocated baseline walking interval (Yellow / Walk 3), 3 synchronization intervals for each respective song (Blue / Walk 1) and 3 free walking intervals for each respective song (Red / Walk 2). Lines represent same channels and wavelengths as *Figure 5*.

Accelerometer

The accelerometer effectively recorded head movement in all planes and directions and correlated with the intervals of baseline, synchronized, and free walking for all 3 participants across all 3 trials.

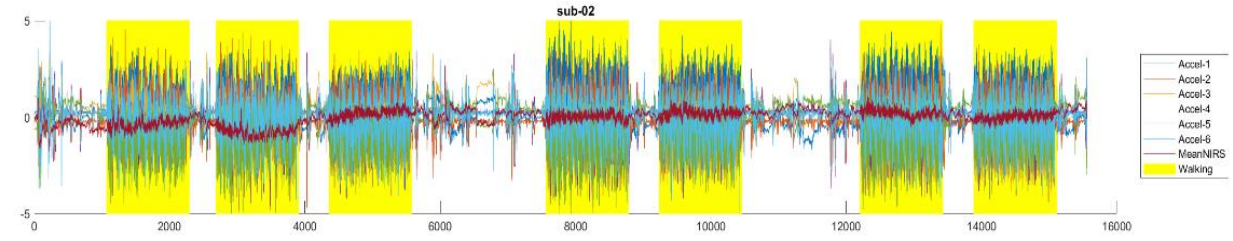

***Figure 7:* Accelerometer Recording for Participant 2**

Yellow highlights show the same baseline walking and then the synchronized and free walking intervals across the 3 trials. Red line through middle shows mean activity for all channels at both wavelengths whose activity can be seen to increase in conjunction with the 2 directions of movement for each *X*, *Y* and *Z* planes.

Motion Correction with SplineSG

SplineSG was seen to be the only effective method for motion artefact removal, working most prominently for participant 1 and participant 2, while participant 3 had inconsistent raw signals to begin with (*Figure 6*). SplineSG effectiveness for participant 3 was therefore less certain.

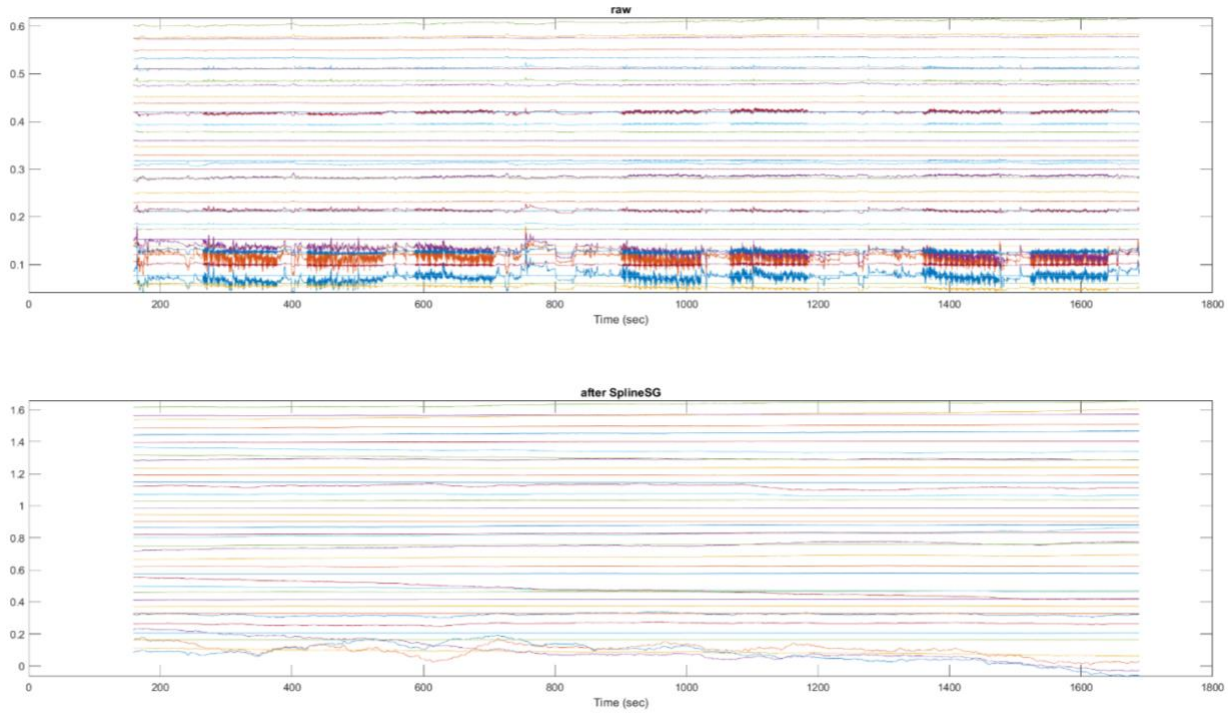

Figure 8: **Participant 2 Motion Artefact Removal**

Top graph displays raw data across all channels and wavelengths with prominent motion artefacts. Bottom graph displays same channels across all wavelengths aver SplineSG, effectively removing a significant proportion of motion induced activity and isolating potential indications of cortical activity.

Correlational Matrices for HbO and HbR

The pre-processing pipeline resulted in interpretable correlational matrices for HbO and HbR levels, although low statistical power prevented any significant interpretations. Participant 1 and Participant 2 both displayed respectable anticorrelations while participant 3 was evidently incorrect but for unknown reasons.

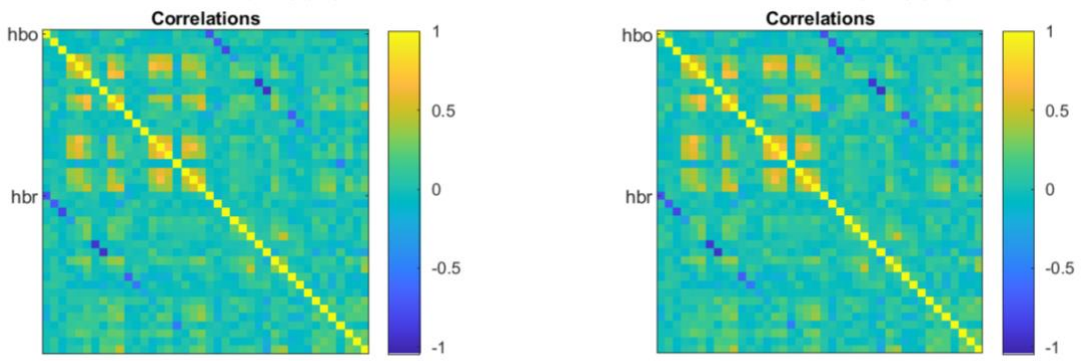

Figure 9: **Correlation of HbO and HbR for Participant 1**

HbO (yellow diagonal) and HbR (mirrored blue diagonal's) demonstrate a prominent anticorrelation within a respective channel. Individually, the top left pixel represents Channel 1 and its correlation with itself for HbO concentration (the 850nm wavelength). There are 20 pixel rows and columns representing each individual channel and its HbO correlation with itself (this creates yellow diagonal). HbR concentrations (the 760nm wavelength) begin halfway down and demonstrate each channel and its HbR correlation with itself (this creates blue diagonal). Pixel 21 in the first column represents this HbR correlation for Channel 1. Left matrix is sampled at 1/60 Hz. Right matrix is resampled back at 1 Hz.

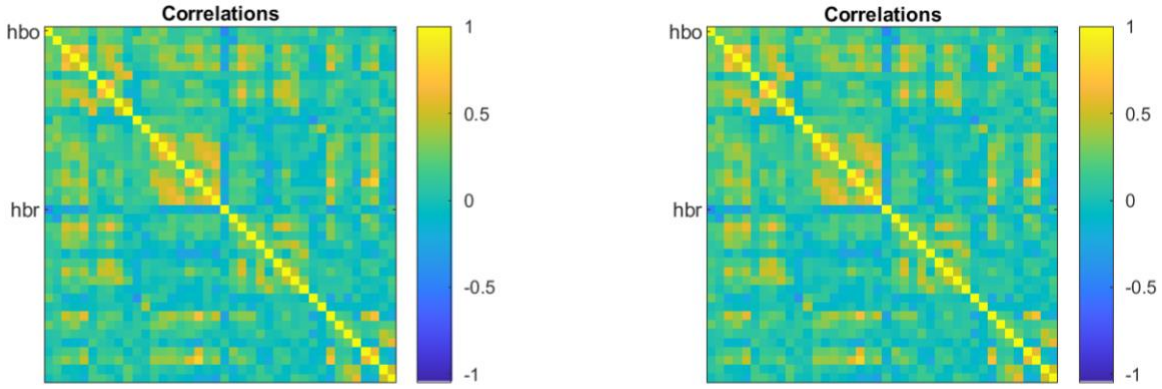

Figure 10: **Correlation HbO and HbR for Participant 3**

HbO (yellow diagonal) is evident for all channels at the 850nm wavelength, however, no anticorrelation is seen with HbR (absence of mirrored blue diagonal). Left matrix is sampled at 1/60 Hz. Right matrix is resampled back at 1 Hz.

General Linear Model Correlations on Motor Montage Layout

Comparisons between HbO and HbR levels and between baseline, synchronized and free walking resulted from GLM contrasts. When comparing group-level results between the baseline walking and the two experimental walking conditions, inconsistent HbO and HbR anti-correlations were seen on an individual channel level represented on the 8 x 8 motor montage

layout. Notably, proper anticorrelations were seen in the left hemispherical montage between S1-D1, S1-D2, S1-D3 channels and right hemispherical montage in the S5-D5 channel. Poor anticorrelations were seen in most other channels across both hemispheres, a notably poor channel being the S5-D6 channel seen in the right hemisphere.

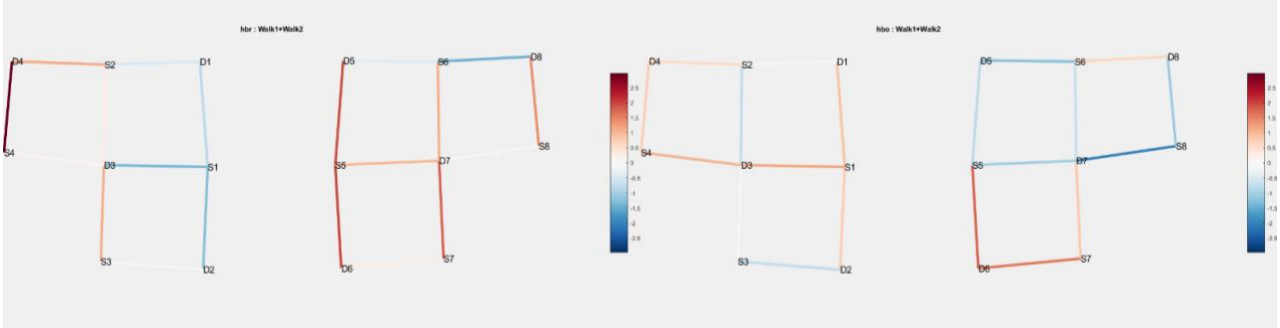

Figure 11: **Experimental Walking vs Baseline Walking**

Proper anticorrelation seen between S1-D1, S1-D2, S1-D3 and S5-D5 channels in HbR (left montage) and HbO (right montage). The left hemisphere is shown on the left side and the right hemisphere on the right side, for both HbR and HbO layouts, respectively.

When comparing group level results between synchronized and free walking conditions amidst music, inconsistent and insignificant channel anticorrelation was seen once again. The only significant channel to mention, which demonstrates a proper anticorrelation between HbO and HbR within this comparison and within the experimental walking versus baseline comparison, is S5-D5.

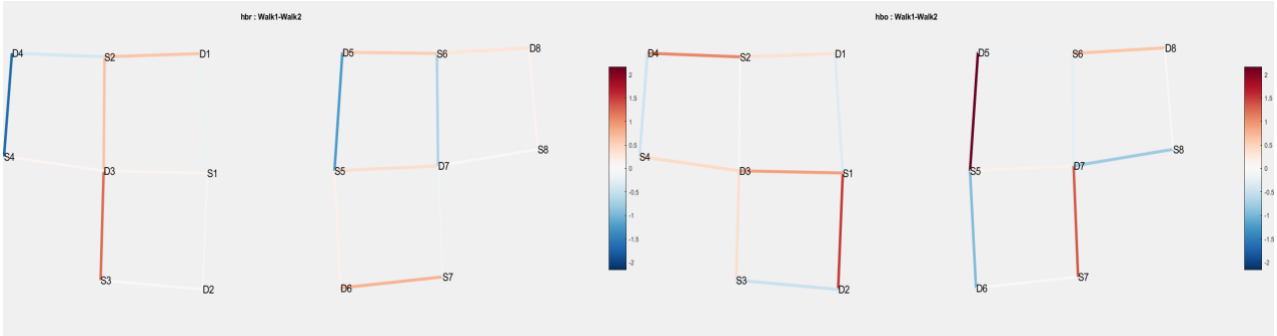

Figure 12: **Synchronized Walking vs Free Walking**

Proper anticorrelation seen most prominently in S5-D5 channel between HbR (left montage) and HbO (right montage). The left hemisphere is shown on the left side and the right hemisphere on the right side, for both HbR and HbO layouts, respectively.

Gait Results

The initial preprocessing of the pressure sensor walkway was successful. Footsteps were accurately recorded and any left-foot or right-foot discrepancies were corrected accordingly, however, characteristics such as stride length, width and velocity have not yet been analyzed. Unfortunately, the actual time correlated analyses of gait trends in conjunction with fNIRS activity during the trials has also not yet been completed.

Discussion

Descriptive Data

When observing the channels across the motor montage layout, if the anticorrelation between the HbO and HbR readings are present, the hemodynamic reading can be interpreted as the respective difference in activity within that respective region during experimental walking compared to silent baseline walking (*Figure 11*) or synchronized walking compared to free walking (*Figure 12*). For *Figure 11,* the activation in a particular channel could therefore be considered the difference in activity between, at a minimum, walking with music and walking without it. For example, the S5-D5 decrease in HbO within the right hemisphere in *Figure 11* suggests a decrease in activity within this region during the experimental walking compared to the baseline.

For *Figure 12,* however, because this is looking at the effects of synchronization compared to free walking, to isolate the effects of synchronization, the channel in focus must also be anticorrelated in *Figure 11*. This ensures the effect is task dependent (the demand for synchronization) and not due to just walking or the presence of instrumental music. In other words, by subtracting the baseline activity changes in the initial experimental walking versus baseline walking comparison (*Figure 11*) from the synchronized versus free walking comparison

(*Figure 12*), the walking induced activity and general effect of the music is eliminated, thereby isolating potentially synchronization induced activity. Channel S5-D5 is the only example of this as the proper anticorrelation is seen in both comparisons displayed in *Figure 11* and *Figure 12*. A significant increase in HbO levels in the S5-D5 channel (*Figure 12*) potentially suggest an increase in activity during synchronized walking compared to free walking. The region of brain covered by this channel can be hypothesized as the right medial SMA and/or the primary motor cortex (M1). In sum, these results could suggest that synchronization of gait to an instrumental music piece causes an increase in activity with the supplementary and primary motor cortices compared to free walking with the same music.

Feasibility

Limitations

In this feasibility study we attempted to combine the dynamic features of fNIRS with a pressure sensor walkway in the context of a synchronization versus free walking task paradigm when listening to instrumental music pieces. The limitations span across the paradigm structure, physical instrumentation used, population pool and the data processing methods of this pilot study.

Firstly, only two of the survey respondents came for the in-person session of the experiment, meaning that the familiarity, groove, and enjoyment mean scores were only applicable to two thirds of the in-person experimentation participants. The one individual who came in short notice and did not complete the survey may have had differing survey results which, with such a small participant pool, could have changed the overall results determining which songs were chosen for the experiment. Although we recorded BAT data to determine which participants were good beat perceivers and bad beat perceivers, only group level effects

were compared within the GLM and displayed on the motor montage layout of HbO and HbR activation (*Figure 11, 12*). This prevents any between-subjects analysis of any underlying differences in gait characteristics or neural activity caused by an individual differences in beat perception ability.

Secondly, the paradigm structure itself had many faults, especially within the Psychopy programming. Although there were some triggers to define task intervals with the respective brain activity, they were not placed consistently and therefore the pre-processing of fNIRS data required estimations of task intervals and rest intervals based on the observed activation levels. Moreover, no randomization was implemented for the order in which the songs were played nor the order in which synchronized walking or free walking occurred. Furthermore, the cadence of the songs was also not adjusted in any manner. Adjusting the cadence has been observed as an important element to reduce the potential of participant's having a natural gait tempo which automatically synchronizes with the beat (Ready et al., 2019).

Thirdly, the songs were only connected with the Psychopy program which was only connected to the fNIRS device and its Aurora program. This meant that the gait mat recording data had no synchronization with the respective timing intervals of the tasks and the corresponding fNIRS data. Unless manually superimposed onto each other to assess any potential correlations between gait trends and cortical activity, analyses of the behavioral effects and cortical activity remain separate for now. Connecting and synchronizing these two recordings is a process which has never been done before and therefore the technology or coding needed to connect these two methodologies must still be explored for interpretations of these results to ensue.

Fourthly, the aforementioned cadence adjustments for the songs could have been useful not only for isolating synchronization from natural gait cadence, but for controlling for fast paced beats which cause participants to begin sweating. These physiological measures are important because as discussed previously, increases in heart rate during high paced movement can be picked up in the unavoidable scalp signal during recording (Herold et al., 2017, 2018).

Finally, although SplineSG was effective at removing most of the motion artefacts, it came at the consequence of preventing the correction of temporal autocorrelations. Temporal autocorrelations refer to the idea of a variable at one point in time being correlated with itself at another point in time. For example, if we were to look at the HbO concentration of a specific channel such as S5-D5 mentioned earlier, a temporal autocorrelation veering towards 1 suggests that the HbO concentration seen at 10 seconds into the trial, has a lingering effect on the HbO concentrations seen at 0.1, 1 or multiple seconds later. A temporal correlation near zero suggests that the HbO concentration at a particular timepoint is not being affected by its concentration from 1 second earlier nor is it effecting the succeeding concentration reading. A temporal autocorrelation at zero is desirable because we want to be sure the signal which we are interpreting is present because of something such as walking or synchronization, not because a strong signal was present beforehand. In the absence of SplineSG, this temporal autocorrelation is properly controlled for. However, this prevents the correction of the data for motion artefacts which are so prominent in a gait study such as this. We could therefore only control for one element at a time and in this study, the temporal autocorrelation was left unchecked because controlling for the motion artefacts were deemed more important in this scenario.

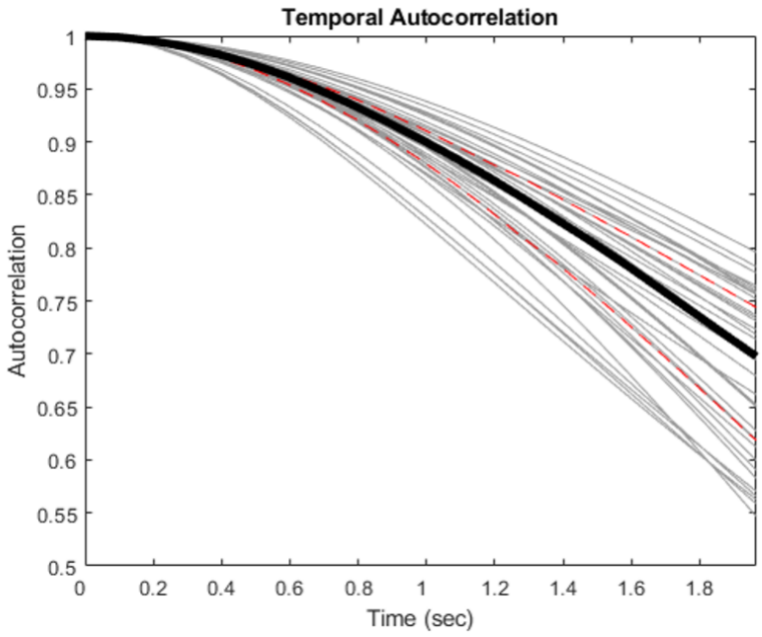

Figure 13: **Bad Temporal Autocorrelation Caused by SplineSG**

Variable has full correlation with itself at Time = 0 and significant correlations with itself across multiple later timepoints. Each individual moment is affected by not only the stimulus but the level of activation from the preceding and succeeding moments.

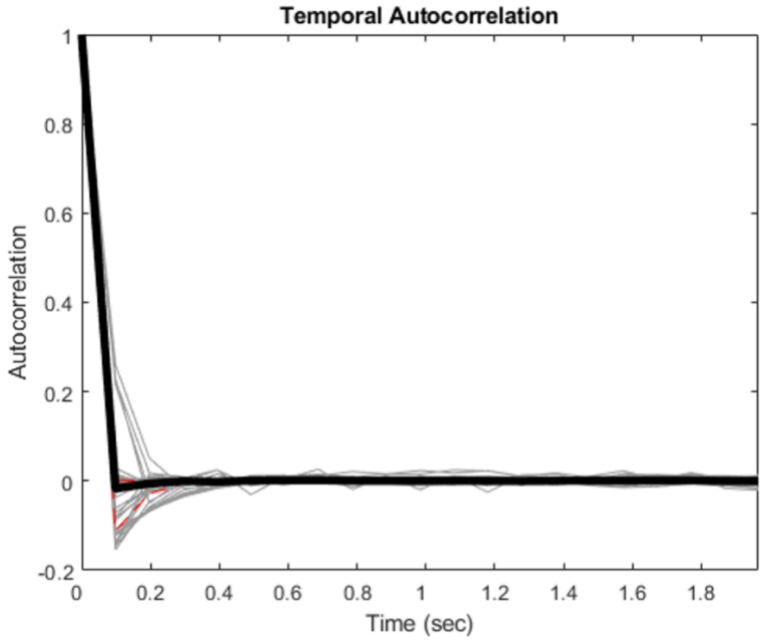

Figure 14: **Good Control of Temporal Autocorrelation in Absence of SplineSG**

Variable has almost no correlation with itself at any other timepoints except for at Time = 0. Each individual moment is affected only by the stimulus causing the recorded activation at that moment, not by its level of activation from any preceding or succeeding moment.

Future Study

Considering all these limitations, a future study can hopefully improve these elements to produce results which a more reliable, valid, and even statistically significant. To begin, a larger participant pool could be used as fNIRS is not selective in eligibility criteria and the paradigm structure of walking is not very exclusive. A larger participant pool would allow for more statistical power which could lend itself in determining the appropriate songs, analyzing group differences between good and bad beat perceivers, and discovering any potential group-level synchronization effects for gait characteristics and cortical activity. A larger song pool could also be beneficial as the songs available for selection in this study were approximately 10 years old or more. Having a more diverse pool of stimuli could identify ideal songs for maximizing underlying familiarity, groove and enjoyment effects and achieve mean scores for the selected songs which are representative of a greater majority of the population.

A more robust Psychopy paradigm could also be implemented to aid in multiple ways. Firstly, it could have more definitive triggers for defining each time interval of baseline, synchronized and free walking as well as the rest intervals in between. Secondly, Psychopy may be the method best suited for synchronizing the PKMAS program used for gait mat recordings and the Aurora program used fNIRS recording. If one holistic system was created, recording for both programs could begin simultaneously for each task interval, allowing for analyses to be done regarding any correlates between gait characteristics and cortical activity. Thirdly, the sequencing of the instrumental songs and the synchronization and free walking intervals could all be randomized to control for any learning effects or participants continuing to free walk or synchronize into the other task interval.

Physiological artefacts could be controlled for using multiple methods as well. Firstly, short-channels could be implemented into the montage setup of the optodes on the fNIRS cap. Short-channels reduce the depth in which the near-infrared light penetrates the head, allowing for an isolated recording of the hemodynamic response from the scalp instead of cortical activity (Goodwin et al., 2014). A smart watch could also be worn during trials to track different physiological signals such as heart rate. The alternative and more robust option is NIRxWINGS (see Appendix A) which, when worn, can track physiological data such as temperature, respiration, heart rate and galvanic skin response. All three of these tracking methods could allow for physiological signals to be removed from the cortical signal, thereby isolating the activity representative of cortical activity and not any parallel physiological responses.

Preceding a future study, a broader literature review could also be done to identify further motion correction methods which can effectively remove motion artefacts while not leaving temporal autocorrelation unchecked either. Data from this current pilot study could be used to test the effectiveness of these methods so that this roadblock is avoided during data pre-processing and statistical analyses of the next study.

Conclusion

In sum, the combination of fNIRS and a pressure gait mat is feasible, but a variety of limitations need to be considered to achieve reliable, valid, and ultimately significantly correlated results. A future study that implements the necessary changes stated above could accomplish this goal and produce results that become relevant within the realm of gate research. Although healthy participants may be the most feasible for initial succeeding study, an attempt at recruiting PD patients could be made in the future to understand potential differences in the neural correlates of gait synchronization between healthy and PD individuals. Overall, these

studies could gain a more detailed understanding of the contexts in which utilizing RAS and SMS have maximal effects for alleviating gait impairments and subsequently reducing the frequency of falls and injury.

Appendix A

General Gait Mat Specs

16-foot (4.88m) pressure sensitive walkway from Zeno™ (see Ready et al., 2019)

Gait Mat General Protocol

Qualtrics Survey Results

Survey Results Link

Cleaning Probes

Cleaning Probes Link

Aurora User Guide

https://drive.google.com/file/d/1KGuX0vZpEeCJlp1KY9NpkqXLJNN5QwdM/view?usp=sharing

Cap Selection and Placement

https://drive.google.com/file/d/1ZJhvZB08tIOwxQ0qRhPBVMI-pR2P5wJ5/view?usp=sharing

NIRxWings

https://nirx.net/wings

Appendix B

Standard Operating Procedure for NIRSport 2

1. Make necessary measurements for individual's head to acquire knowledge to choose cap size (see ***Cap Selection and Placement*** in Appendix A*)*.
2. Have individual put on the small backpack to hold the NIRSport 2.
3. Connect source and detector cables into their respective slots on the NIRSport **before** turning on device and **before** opening Aurora. ******When using an accelerometer especially, proceeding in a different order of operations can potentially impair accelerometer optimization and setup in Aurora later******
4. Place device into the backpack.
5. Before inserting each source or detector, using small lighted probes to push aside hair and reveal scalp to ensure a strong connection and reduce interference.
6. Slowly connect each source and detector to their respective holes in the cap depending on the montage being used
7. Using trees to organize each individual source and detector wire is very helpful for not just efficiency but to reduce entanglement and potential movement and tugging during experimentation.
8. Now open Aurora **before** turning on the NIRSport
9. With Aurora open, now turn on NIRSport, connect to device in the desired manner and proceed to select the desired montage.
10. Ensure this montage has the proper selections for accelerometer before continuing.

11. Optimize the channels once the montage has been selected and attempt to improve any poor channels by removing the respective source or detector and moving any lingering hair in the way of the scalp.

12. If optimization is consistently poor, a shower cap to cover all the sources and detectors may aid in eliminating the effects of external light coming from the room or elsewhere.

13. After optimization is complete, go to the accelerometer tab and configure it accordingly so that it responds accurately to the individual's head movements.

14. Proceed with recording.

15. After completing the experiment, turn off the NIRSport and remove all sources and detectors.

16. After the individual has left, proceed with proper sanitization of the source and detector small black plastic caps (see ***Cleaning Probes*** in Appendix A), and wash the full head cap.

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