The Use of NIRS in Monitoring Lower-Limb Motor Activation: A Study Comparing a Mobile and Research-Grade System

by

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ABSTRACT

Near-infrared spectroscopy (NIRS) is an optical imaging tool used to monitor neural activation through detecting changes in oxygenated and deoxygenated hemoglobin. This study aims to determine whether NIRS can be used to monitor neural activity associated with lower limb movements, as well as comparing the capacity to do so between a research-grade and mobile system. This marching task used was expected to elicit medial neural activity in the sensorimotor cortex. The blocks in this study differed based on the system used (NIRScout or Axem), as well as the position placement of the mobile device. Both devices showed changes in activation associated with lower limb moments. The research-grade device showed a greater capacity to detect change in activity, and the mobile device showed more expected patterns of activation for lower limb movements. Knowledge gained from this study contributes to the development of mobile NIRS systems in monitoring motor-related neural activation.

LIST OF ABREVIATIONS USED

NIRS	Near Infrared Spectroscopy
EEG	Electroencephalogram
BOLD	Blood Oxygen Level Dependent
ROI	Region of Interest
HbO	Oxygenated Hemoglobin
HbR	Deoxygenated Hemoglobin
LED	Light Emitting Diode
DPL	Differential Path Length
MBLL	Modified Beer-Lambert Law
CoG	Center of Gravity
TMS	Transcranial Magnetic Stimulation
GLM	General Linear Model
MI	Motor Imagery
HRF	Hemodynamic Response Function

DISCLOSURE STATEMENT

This experiment was completed in conjunction with members of the Axem Neurotechnology team, who assisted in development of software used to control the mobile headset, as well as providing us with access to the prototype device used in the experiment. There was no financial support provided by Axem Neurotechnology or any members of the company. Assistance was obtained from members of the team in designing the experiment, as well as for correcting and technological issues that arose from use of the mobile device. It has been acknowledged that the results of this study may have financial implications for Axem Neurotechnology, and thus members of Axem Neurotechnology were not involved in any analysis and did not contribute directly to any results of this study. It should be noted that none of the main researchers involved in this study had any financial incentive in the outcome of this study.

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CHAPTER 1 INTRODUCTION

The use of optical principles in physiological and neural research dates to the late 1960s (Ferrari & Quaresima, 2012) when light was first being used to understand basic composition of intact tissues (Chance et al., 1962). Although it was initially useful for performing non-invasive analyses, only a single light source and detector were used, thus limiting tissue coverage. As the technology developed, practical uses included analysis of skin oxygenation in infants (Ferrari & Quaresima, 2012; Lloyd-Fox et al., 2010; Meek, 2002), prevention and treatment of seizures (Sokol et al., 2000; Steinhoff et al., 1996; Watanabe et al., 1998), stroke rehabilitation (Arenth et al., 2007; Lin et al., 2009; Mihara et al., 2013; Saitou et al., 2000; Terborg et al., 2004), and monitoring neural activity associated with psychiatric conditions like depression (Kameyama et al., 2006; Suto et al., 2004) and schizophrenia (Fallgatter & Strik, 2000; Kubota et al., 2005; Suto et al., 2004). More recently, optical spectroscopy using infrared light has been used in determining concentrations of oxygenated and deoxygenated blood within the cortex of the brain (Alkadhi et al., 2002; Ferrari & Quaresima, 2012; Firbank et al., 1998), which has since been referred to as Near-Infrared Spectroscopy (NIRS). By measuring oxygenation, inferences about the underlying neural activation can give insight into brain function (Meek, 2002; Strangman et al., 2002; Villringer & Chance, 1997).

Compared to other optical imaging devices, NIRS has mainly been used for research applications; however, with development it has demonstrated initial promise for clinical application as a stroke rehabilitation tool (Arenth et al., 2007; Lin et al., 2009; Mihara et al., 2013; Saitou et al., 2000; Terborg et al., 2004) because of some potential advantages it provides over other conventional tools such as EEG and MRI, such as ease

of use and portability (Aslin & Mehler, 2005; Lin et al., 2009; Yang et al., 2019). These developments have included increases in portability of the device and an increased capacity to withstand noise artifacts caused by the movements of device users (Lin et al., 2009; Yang et al., 2019). More recently, NIRS devices have been developed to be self-contained within a wireless headset, allowing for both easy transportation of the device, and ease of use for users while performing a wide range of physical movements (Axem Neurotechnology; NIRx Medical Technologies; Artinis Medical Systems).

Technological advances being made to improve the data collected from NIRS devices face a balance of cost versus utility. NIRS devices have become incrementally better in terms of accuracy, coverage, and sampling rate; however, these improvements often come at the expense of an increased overall cost of a device. This tension between utility and cost has driven the development of a wide range of devices created based on intended use and purpose. Devices targeted for research-based use require significant versatility in layout configurations while maintaining a high level of data quality (i.e., high signal to noise ratio). The NIRScout developed by NIRx is an example of a system targeted for research that falls on the high-cost end of the spectrum. On the other end, for devices that will be used in a clinical or rehabilitation setting, cost effectiveness, portability, and ease of use need to be emphasized to improve the user experience. Companies such as Axem Neurotechnology have focused on the creation of lower cost devices intended for a single specific use and user. Axem Neurotechnology's target is neurofeedback for motor rehabilitation following stroke. Neurofeedback involves measuring an individual's brain activity and presenting it back to them with the intention that they may use this information to modulate the neural activity. For this clinical

application, the goal is for the device to have enough capability to reliably measure brain activity in the motor regions of the brain while keeping the overall cost of the device low and the size of the device small, allowing it to be more accessible to more users.

Regardless of whether a high-cost research grade device or a portable clinically targeted device is being used, one of the major limitations of NIRS technology is how deep in the cortex it can measure. The path that light takes during NIRS is directly dependent on the spacing between sources and detectors. NIRS models predict that the path that light takes while using source-detector spacing of 3 cm measures only a few millimetres deep in the cortex. While path lengths greater than 3 cm may reach deeper, there will also be a decrease in signal to noise ratio, which has the potential to decrease the usability of data collected (Brigadoi & Cooper, 2015; Goodwin et al., 2014; Huppert et al., 2009). Because of this limitation, there is a need for careful consideration regarding whether the use of NIRS is appropriate for a given research question or application.

Due to its location 2.0-4.5 mm below the skull in the brain , the sensorimotor cortex is typically a good candidate for measurements using NIRS. However, the somatotopic representation of the lower limbs, with the thighs, calves, and feet, are located on the longitudinal fissure (Saunders, 2019) which reaches deeper into the brain than the rest of the motor cortex. This may mean it may be more challenging to detect activation within this region. Previous work has demonstrated it is possible to distinguish between different motor regions being activated during gait divided into arm swings and leg movements (Miyai et al., 2001). However, this study and most other studies looking at motor regions using NIRS, often perform a group analysis drawing only conclusions at a group level (Koenraadt et al., 2012; Koen L.M. Koenraadt et al., 2014; Miyai et al.,

2001; Nishiyori et al., 2016). Group level conclusions become problematic when trying to implement NIRS as a rehabilitation device for a single user due to the lack of evidence that a group level outcome applies to all individuals within the group. Knowing that using NIRS with individual patients is a desired outcome, it stands to reason that research should explore whether NIRS is appropriate to monitor lower limb activation within individual users.

The overall aim of this study was to assess and compare the ability of a research-grade NIRS system and a portable NIRS system to monitor the deeper locations of the motor cortex responsible for lower limb movement within individual users. By completion of this study, it should be possible to determine whether an analysis can be performed in a single session, whether it is suitable for only a subset of participants, and whether there are benefits or limitations to using a specific grade of device. Adults, over the age of 50 years (to maintain a consistent age with a post-stroke population), completed a 20-minute session where they alternated between one of three randomized motor tasks and rest. The tasks included right- and left-hand movements and a seated marching task, only the seated marching task is included in the scope of this thesis. Expected regions of activation were predetermined and assessed through use of a general linear model (GLM), allowing for determination of significantly activated channels. Changes in activation were also assessed through comparing the activation while performing the task to rest and comparing between the devices used in this experiment.

Purpose Statements:

1. The first purpose of this study was to test whether a NIRS device can be used to monitor activation in lower limb regions of the sensorimotor cortex of older adults within individual users during a single 20-minute data collection session. The purpose was explored through use of a GLM to determine which channels on the device became significantly activated and comparing them to expected regions of activation (medial channels), as well as assessing the proportion of active channels that became significantly active for a given device. The null hypothesis for this purpose is that the medial region of the sensorimotor cortex will show no significantly active channels for a given device,
2. The second purpose of this study was to compare the ability of a NIRx and Axem device to detect signal change associated with lower limb regions of the sensorimotor cortex of older adults within individual users during a single 20-minute data collection session. The purpose was explored through assessing changes in activation as measured through HbO, between rest and task for a given device, as well as comparing between devices differences of the number of significant channels within expected regions that become active. The null hypothesis for this purpose is that the devices would show similar HbO signal change and have a similar proportion of medial channels active.

CHAPTER 2 LITERATURE REVIEW

2.1 Underlying Principles of Near Infrared Spectroscopy

Optical imaging is the process of shining light through biological tissue, measuring the light that is reflected out, and using this data to infer information about the tissue. Many optical imaging devices have found practical use within fields like physiological research and medicine. An example of an optical imaging device that many people are familiar with is radiography, otherwise known as X-rays. This device uses wavelengths between 0.01 nm and 10 nm, making them invisible to the human eye, but able to pass through some of the less dense tissues of the human body. Other imaging techniques such as near-infrared spectroscopy (NIRS) use light that is relatively close to visible light, making use of wavelengths from 650-900nm. Although these two methods of imaging make use of very different wavelengths of light, they share some commonalities in that they rely on the assertion that light measured after passing through a biological material can be used to image the composition of the tissue itself.

NIRS is often used to measure the oxygenated and deoxygenated hemoglobin within brain tissue as a proxy for neural activation. The first section of the literature review will cover some of the principles that govern how these NIRS devices work in relation to measuring brain activity. This will include a discussion of the differences in application of techniques and principles between NIRS devices designed for different purposes. The second section of the literature review will focus on the specific application of NIRS in measuring movement-related neural activity using both mobile and research-grade NIRS devices.

2.1.1 Light Propagation

As the name suggests, NIRS makes use of light in the near-infrared range, typically using one or two specific wavelengths. When passing light through biological materials, deflection and diffraction occurs, scattering the light (Huppert et al., 2009). While doing so, the overall general path that light takes is relatively predictable, often scattering in curved banana-like shape (Huppert et al., 2009). By placing a light detector at some distance away from the source, it is possible to gain insight into the medium that the light traversed.

Much of the light propagation from a source to a detector is dependent on the composition of the materials being traveled. Biological tissues have varying absorption spectrums dependent on physical and chemical properties of the tissue such as density, molecular composition, or even the physical arrangement of the tissue (Tsai et al., 2001). Absorption spectra are a representation of which wavelengths of light are most or least absorbed by a given material. Because of differences in absorption spectra of different biological tissues, it becomes possible to determine what type of tissue the biological material likely is by detecting the amount of light that is not absorbed by the tissue at specific wavelengths (Tsai et al., 2001). However, due to overlap in some absorption spectrums, it can become difficult to fully differentiate multiple biological tissues in close proximity without advanced calibration techniques (Newman, 2019).

Absolute concentrations and compositions of biological tissue can be useful depending on the given need of a researcher or clinician; however, it is not necessary to take advantage of NIRS technology. The non-static nature of tissues and molecules within the human body make it possible to observe changes over time. One of the most dynamic tissues in the human body is blood, circulating though the body several times a

minute (Saunders, 2019). Within the blood exists high concentrations hemoglobin, a molecule that has an absorption spectrum that is dependent on its state: oxygenated or deoxygenated (Huppert et al., 2009; Newman, 2019) This makes it possible to monitor how the concentration of each state of hemoglobin changes over time, with more absorption being indicative of higher concentrations of a given molecule and less absorption showing lower concentrations. Although this is not a direct measure of hemoglobin concentrations, the information can be used to make inferences about the underlying neural activation that is occurring based on change in absorption over time (Meek, 2002; Strangman et al., 2002; Villringer & Chance, 1997). The exact relationship between changes in hemoglobin concentrations and neural activity is further discussed in a later section (2.1.3 Wavelengths).

2.1.2 Sources and Detectors

In NIRS, sources will shine light directly into the tissue of interest (usually perpendicular to the surface of the tissue). Sources make use of light in the near-infrared range. The exact wavelength within the near-infrared spectrum is selected based on the tissue to be measured and the tissues in the body with overlapping absorption spectrums (discussed in further detail in the following section, 2.1.3 Wavelengths). The type of source can vary depending on the device being used. The two most common sources used are LEDs and lasers. These types of sources differ based on specificity of the wavelength being emitted, the spacing achievable based on size, the depth to which they are effective, and the portability of the devices that control the sources (Irani et al., 2007). A detailed discussion of the advantages and disadvantages of each type of source are beyond the

scope of this review. Both devices being used in this study make use of LED sources. LEDs are commonly used due to their relatively inexpensive cost and simplicity of the controllers that operate the LEDs.

The detectors used in NIRS are otherwise known as photodiodes and also range in quality. Together, a source-detector pair is commonly referred to as a channel. Many factors contribute to the quality of detector such as the sensitivity, the dynamic range, and the maximum achievable sampling frequency (Dix et al., 2013). The sampling rate can have an influence on how the data is acquired. In the case of some high-end photodiodes, it becomes possible to record data in the range of picoseconds which allows for discrimination between light that originated at the same source and time but traveled further distances and thus longer times, allowing for greater location specification (discussed more in section 2.1.4 Types of Data Acquisition). However, these types of detectors are often very costly. More commonly, NIRS devices will use photodiodes recording in ranges from a tenth to a hundredth of a second, as this requires less costly parts and does not require time- or frequency-domain analysis. With relation to this study, the NIRScout by NIRx Medical Technologies makes use of Si Avalanche Photodiodes, capable of achieving picosecond sampling, while the Axem device makes use of photodiodes that are unable to achieve this type of precision. However, for the purpose of this study the NIRScout will be used in continuous sampling mode which is comparable to the photodiodes used by the Axem device (sampling modes discussed in more detail in section 2.1.4 Types of Data Acquisition).

2.1.3 Wavelengths

When conducting spectroscopy, it is important to consider what wavelength of light is being used due to the differing absorption spectrums of materials. The tissues that compose the human body have ranges of wavelength that they readily absorb (Newman, 2019), meaning specific wavelengths may or may not reflect off a tissue based on its absorption spectrum. For this reason, it is important to consider what tissue types are being analyzed and what other tissues could interfere. Figure 1 shows the absorption spectrum of some tissue types commonly found within the body. Oxygenated and deoxygenated hemoglobin have a relatively wide range of light they are receptive to; however, their absorption coefficient overlaps over much of the range. One range of wavelengths exist (600-900 nm) in which there is a difference between the optical properties of oxy- and deoxygenated hemoglobin. It is therefore possible to distinguish between changes in concentrations of the two hemoglobin types if two different wavelengths of light within this range are used (Newman, 2019; NIRx Medical Technologies, 2013).

For the two devices of interest in this project, the wavelengths are fairly similar with the NIRScout device using 750nm and 850nm, and the Axem device using 740nm and 850nm. While large difference in the specific wavelengths being used can affect factors such as the interference from other tissues, the difference in wavelengths between the two devices is small enough that any effect due to wavelength differences should be minimal.

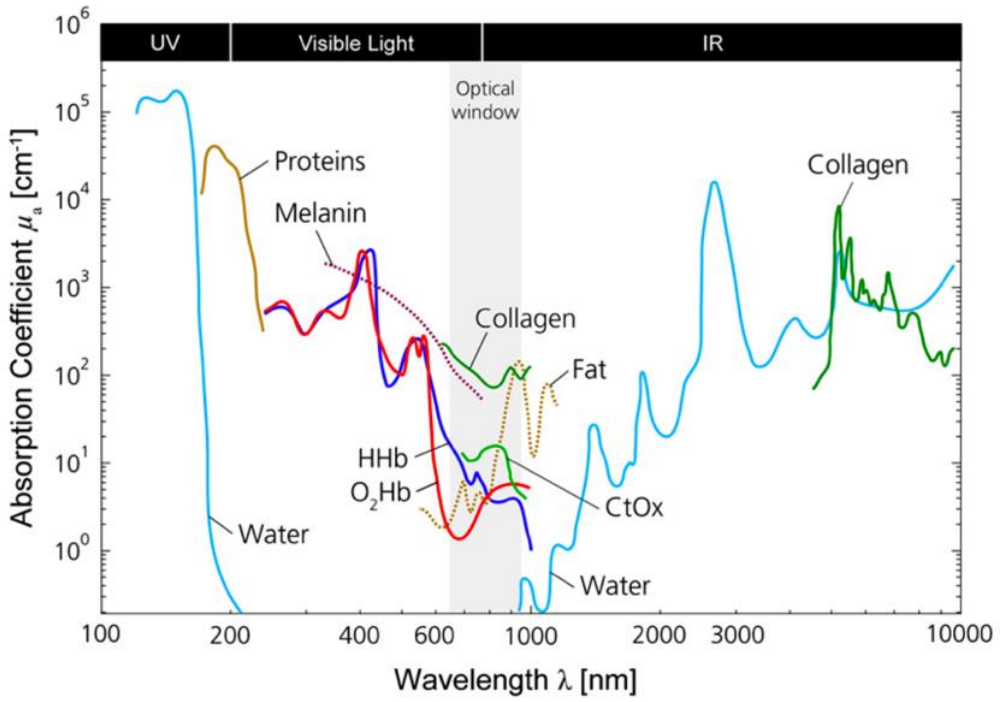

Figure 1 Absorption spectrum of commonly found tissues in the human body. Reprinted from *Research Methods for Cognitive Neuroscience,* by A. Newman, 2019, SAGE.

NIRS is often used to measure the oxygenated and deoxygenated hemoglobin within brain tissue as a proxy for neural activation. While performing motor tasks, motor related neurons become more active and consume more oxygen then at rest. Initially, oxygenated Hb decreases as it is consumed, but then increases to bring HbO to the active tissue. This change in blood oxygen levels can be modeled in what is commonly referred to as the blood oxygen level dependent (BOLD) response, which typically progresses as follows: 2-3 seconds to begin, 6-8 seconds to peak, and 12-20 seconds to return to baseline (Newman, 2019). Studies have identified this response as a means to monitor neural activation occurring in regions of interests (R. Riedl, 2016; Villringer & Chance, 1997).

2.1.4 Types of Data Acquisition

There are multiple ways that NIRS data can be collected depending on the source configuration. Most methods fall into one of three categories: continuous wave, frequency-domain, or time-domain imaging. These methods differ based on how light is used during the imaging, as well as how the data is interpreted. The following will briefly describe these methods.

In continuous wave imaging, light sources are kept on 'continuously' throughout the imaging (sources are in the off state when not in use between recordings, but when relevant detectors are on, they are on throughout the entire recording time). The detectors measure the amount of light being detected during a short sample of that continuity. This method makes use of the Modified Beer-Lambert equation to determine a change in concentration over time (explained in fuller detail in section 2.1.6 Modified Beer-Lambert Law). Continuous wave imaging is one the most commonly used methods for NIRS data collection because it provides some simplicity in terms of the technical aspects of building and running NIRS devices. Both the NIRScout and Axem prototype use this method of data acquisition.

Frequency and time-domain imaging introduce some complexities to how the light is being transmitted as well as recorded and analyzed. Instead of using a constant light intensity throughout the period that data is being collected, frequency-domain imaging uses fluctuations in intensities which can result in phase shifts, and time domain-imaging uses short bursts while recording light intensity and time of arrival of the light. These methods can provide some beneficial utility depending on the needs of the user,

however, typically require more costly parts and complex analyses. The complexities of these methods are beyond the scope of this study but further information about these types of data collection methods can be found in Newman (2019).

2.1.5 Source-Detector Spacing

The spacing of sources and detectors while using NIRS affects the depth of the recording and the signal to noise ratio (SNR) of the readings. Having sources and detectors placed closed together increases the intensity of the light being read at the detector, though the propagation of the light is also much shallower into the tissue. By spacing the detectors farther apart, light propagation occurs much deeper in the tissue, however, there is also a decrease in SNR due to a lesser light intensity reaching the detector. This creates an optimization problem where the goal is to achieve readings that are deep enough to be confident that the data being collected is from the cortex of the brain, but shallow enough as to not dramatically decrease SNR. Studies seeking to find the optimal distance of sources and detectors have determined that a ~3 cm spacing is ideal for allowing monitoring of the first few millimetres of the cortex while still keeping the SNR high (Brigadoi & Cooper, 2015; Kamran & Hong, 2013; R. Riedl, 2016).

One of the concerns introduced when a using a 3 cm spacing is the maximum spatial resolution achievable. Given that the exact path the light travels is unknown and at minimum it must travel at least 3 cm (realistically it travels more due to the curved shape that light is taking), it becomes difficult to determine where within that 3 cm the light is being influenced. With the use of NIRS acquisitions such as time-domain imaging it is possible to achieve more specificity in location (Newman, 2019), however in continuous-wave imaging (used by both the NIRScout and Axem device), this becomes much more

difficult without using sources and detectors that overlap in terms of regions they are monitoring. Although using overlapping sources and detectors is one solution for this problem, it also increases the cost of a device and may not even be necessary for a given purpose. Studies have shown that 3 cm spacing is adequate to achieve specificity of different motor regions in the motor cortex becoming more active while performing movements using upper versus lower limbs (Koenraadt et al., 2012; Miyai et al., 2001; Nishiyori et al., 2016). The exact results of these studies will be further discussed in the context of motor rehabilitation for stroke patients in a later section (2.2.3 Previous Research Using NIRS for Motor Region Monitoring).

While a 3 cm channel length is typical for the main channels used from data collection, short distance channels may help improve signal quality. Short distance channels are sources and detectors that are intentionally placed in close proximity (usually ~0.8 cm). The intended goal of short distance channels is to monitor physiological activity that is not occurring at the level of the cortex. Specifically, the layers of tissue that cover and protect the brain have their own absorption spectrums. Tissues such as vascular tissue above the cortex can have a change in activity unrelated to activity happening in the cortex but rather related to such factors as changes in (Brigadoi & Cooper, 2015; Goodwin et al., 2014). Short distance channels are focused solely on recording data from more superficial tissues. An example of the difference between short- and long-distance channels can be seen in Figure 2, with the source 1 and detector 1 representing a short channel, and source 1 and detector 2 representing a long channel. By subtracting activity measured with the short-distance channels from the long-distance channels it is possible to obtain data that is more representative of the activity occurring

in the cortex of the brain (Brigadoi & Cooper, 2015; Goodwin et al., 2014). Short-distance detectors are a relatively new addition to NIRS analysis and provide increased accuracy and analysis power through removing unrelated activity occurring above the cerebral cortex, however, is not strictly required to obtain useful results from a NIRS analysis (Brigadoi & Cooper, 2015). In this case, both the NIRScout and Axem device are equipped with 0.8cm short distance channels around every source.

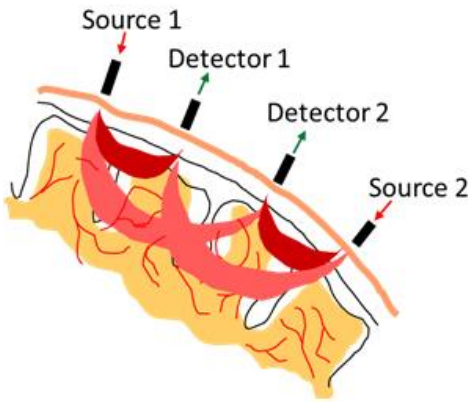

Figure 2 Visual representation of the effect of differing channel lengths on the expected path traveled by light. Reprinted from *NIRScout User Guide*, 2013, NIRx Medical Technologies

2.1.6 Modified Beer-Lambert Law

While performing NIRS, the hemoglobin concentrations are not being measured directly. The raw data collected from any given detector is simply a reading of the light being detected by the sensor over a given period of time. Following light detection, concentrations are calculated based on the Modified Beer-Lambert Law (MBLL) (Cope et al., 1988). The MBLL is a relationship between light absorption and concentration which is used to determine relative changes in oxy- and deoxyhemoglobin

concentrations. Specifically, the MBLL accounts for the scattering of light in biological tissue and makes use of the specific absorption spectrum of oxy- and deoxyhemoglobin. However, there are some limitations due to some of the assumptions made by the MBLL. One such limitation is based on the differential path length (DPL) constant used, which is a constant included to account for how light scatters in biological tissue. The scattering of light, however, is not consistent between individuals, with factors such as age, sex, and wavelength influencing scattering by up to 15% (Newman, 2019). Despite the potential for this to introduce error, it can be minimized through using a relatively limited population range. In the case of this study, the population being used is restricted to individuals over the age of 50, thus any error introduced is likely to be less than the possible 15% (Newman, 2019).

Another limitation of the MBLL is that it assumes uniformity of the tissue and the compounds within the tissues. We know this to not be the case in terms of monitoring the cortex due to hemoglobin being found only within the vessels supplying blood. However, violating this assumption typically results in an underestimation of the concentrations and the values obtained will still be proportional to the true data (Newman, 2019), meaning the violation of this assumption will still provide useful proportional interpretations.

2.2 Research and Clinical Applications of NIRS

2.2.1 Neuroimaging in Stroke Rehabilitation

Following stroke, upper-limb hemiparesis is the most prevalent impairment, often leading to a negative impact on quality of life (Shindo et al., 2011; Zich et al., 2017). One of the focuses of stroke rehabilitation is to facilitate motor task improvements (Caria et al., 2011; Shindo et al., 2011; Zich et al., 2015, 2017). The impact on disability is highly dependent on where the stroke occurred and the severity of the stroke (Mihara et al., 2013). Many individuals often either partially or fully recover motor function following a stroke; however, stroke is still one of the leading causes for disability.

One possible method of stroke rehabilitation is motor imagery (MI) with EEG based neurofeedback. MI is the practice of imagining performing an action and involves many of the same sensorimotor brain regions as physically performing the task (Miyai et al., 2001; Zich et al., 2017). MI has been shown to improve motor performance in a range of fields from athletic performance to rehabilitation (Schuster et al., 2011). One challenge of using MI therapeutically is that it cannot be observed; therefore, it is challenging for the clinician or the individual performing imagery to know whether it is being done effectively. Neurofeedback is the practice of using devices capable of monitoring neural activity in the brain and providing that information to a user in real time through a computer that could provide feedback on the performance of MI. Through combining the practice of MI and neurofeedback, studies have shown that long term motor improvements for stroke patients can be improved (Kranczioch et al., 2014; Mihara et al., 2013; Shindo et al., 2011; Zich et al., 2017).

While a detailed review of neurofeedback is beyond the scope of this report, such a use case provides a rationale for developing less costly neuroimaging systems. Frequent

practice is critical for neurofeedback to be effective due to concerns for its use and benefit that can be achieved in a single sessions (Rogala et al., 2016). Furthermore, for users who are post stroke, shorter and more frequent sessions may produce better training results as long sessions of neurofeedback could be particularly fatiguing for this population and prove to be frustrating given the difficulty of achieving positive results in the task (Street et al., 2015).

With the high number of sessions required to potentially produce improvements for a clinical population, consideration needs to be made for where these sessions would take place. Frequent neurofeedback sessions in a hospital or other clinical setting would be cumbersome for the patient to make travel arrangements, especially given mobility issues. This concern has incentivised the shift towards more mobile and low-cost devices being developed by companies such as iMotions and NeuroScan, who have developed EEG based headsets for home use.

Although many improvements have been made to increase the feasibility of portable EEG devices for home use neurofeedback, there are still some limitations that are associated with these devices. Specifically relating to EEG, there are some concerns about what is required from the users of the devices. To explain, EEG is inherently considered to be very noisy due to the nature of the type of data being collected (electrical signals) (Vorobyov & Cichocki, 2002), and are largely influenced by electrode preparation which can affect impedance. These electrical signals are influenced by external sources of electronics, as well as influenced by motion artifacts. Some measures have been taken to try to improve electrical impedance and improve SNR by using methods such as applying electrically conductive gel, improving the connection between

the scalp and device. However, for a post-stroke population this can be overly challenging to try and implement on their own due to physical impairments, possibly causing a decrease in adherence to the rehabilitation practice (Street et al., 2015).

2.2.2 NIRS as a Potential Alternative to EEG-based Neurofeedback

Mobile NIRS systems may provide an alternative to EEG for measuring movement related activity for neurofeedback. First, NIRS does not require the use of electroconductive gel, or any gel. As mentioned previously, electroconductive gel can result in a decrease adherence to the rehabilitation practice, thus its removal would be beneficial to patients. Secondly, given what is required from neurofeedback, the device being used should have the capacity to monitor the required areas with some level of precision. This is to say, a device should be able to determine whether activation is occurring, and whether the activation that is occurring is happening in the expected regions of the brain. In terms of motor rehabilitation, this would be specific to the motor cortex, with the capacity to distinguish between motor activation related to different regions of the body. The following sections will discuss some of the physiological characteristics and research that has been done using NIRS to monitor sensorimotor related activation.

2.2.3 Previous Research Using NIRS for Motor Region Monitoring

It is widely accepted that the control of movements can be mapped to relatively specific sections of the motor cortex. In general, the proportion of the motor cortex dedicated to a given motor region is correlated to the number of muscle fibers and the

complexity of motor actions required by a given limb (Alkadhi et al., 2002). Figure 3 shows a visual representation of the motor cortex layout in relation to the amount of space given to specific regions of the body. Regions with complex movements – such as the lips for talking – occupy more space on the motor cortex whereas other limbs such as shoulders and arms (not including hands) which are more commonly associated with gross and relatively less precise movements have less coverage of the cortex. Another aspect of the motor homunculus is the medial portion where the motor cortex continues along the longitudinal fissure. This section of the motor cortex is deeper than the rest of the motor cortex, which may be difficult to measure using NIRS due to the typically shallow ranges the device records from. Notably, this region of the motor cortex is associated with the lower limbs (i.e., thighs, legs, and feet).

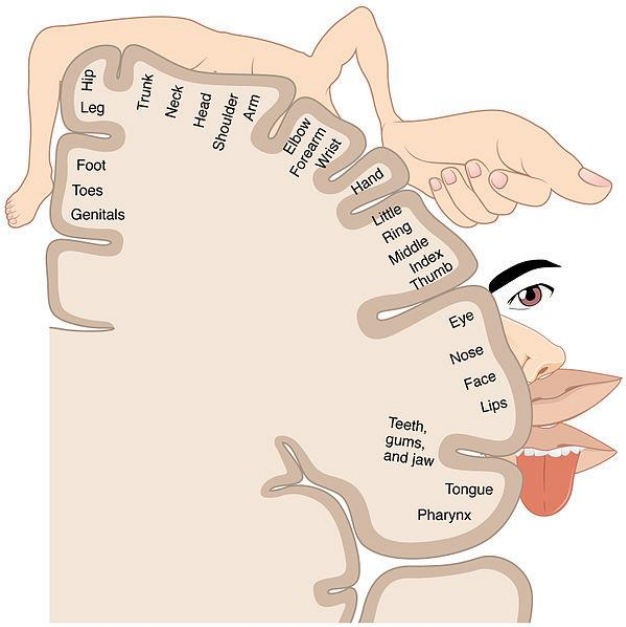

Figure 3 Somatotopic layout of the motor cortex. Reprinted from *Boundless Anatomy and Physiology* (n.d)

The question of whether NIRS is suitable to monitor lower limb neural activation has been explored with some promising results. Studies conducted by Koenraadt et al. (2012), Miyai et al. (2001), and Nishiyori et al. (2016) have explored the use of NIRS to discriminate different motor actions such as hand movements from foot movements. The following will cover each study, addressing what can be concluded as well as some of the limitations on those conclusions.

Miyai et al., (2001) was one of the earliest studies to explore the measurement of different motor regions of the cortex using NIRS, specifically the activation patterns of the different components of gait. A 30-channel system using 9 laser diodes and 12 detectors was used to measure four conditions based on the gait walking pattern: complete gait, arm swings only, leg movements only, and gait imagery. Participants were asked to perform each task on a treadmill for 32 seconds followed by 32 seconds of rest which was repeated consecutively 5 times for each condition. Data collected was used to generate heat maps at the group level (Figure 4) to visualize the activation associated with each condition. Critically, what was observed is that it is possible to observe differences between activation patterns of upper arm swings versus leg movements, with leg movements showing more medial activation patterns than arm swings. It was also possible to conclude that the gait imagery produced similar activation patterns to the complete gait condition, with the differences of activation mostly being observed in terms of magnitude and not spatial location. As one of the earliest studies to begin to characterise activation of gait patterns using NIRS, this study was able to show that gross motor movements can be distinguished using NIRS.

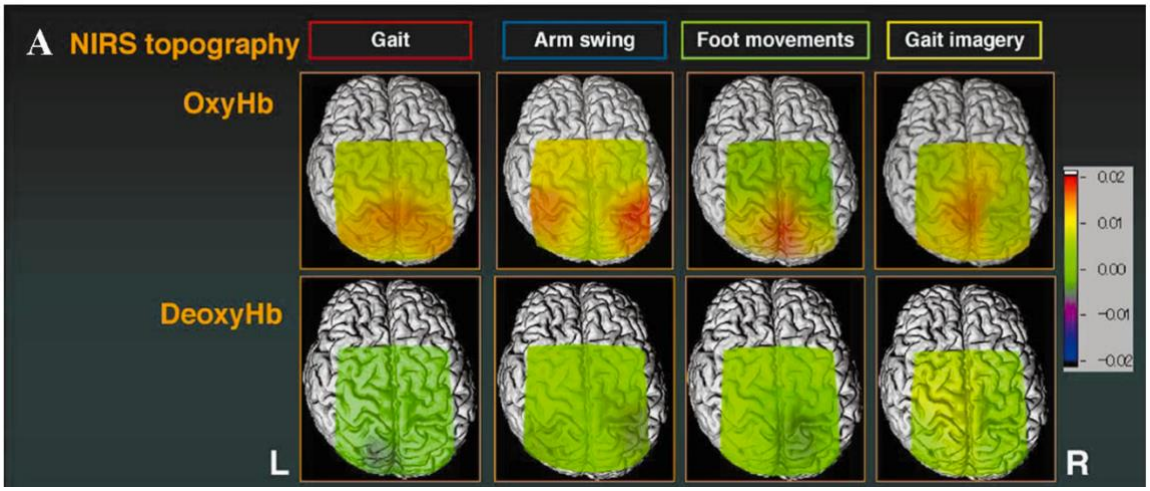

Figure 4 Cortical activation patterns observed based on experimental conditions. Regions in red indicate increases in oxyhemoglobin and regions in blue show lower levels of deoxyhemoglobin. Reprinted from *Cortical Mapping of Gait in Humans: A Near-Infrared Topography Study* by Miyai et al., (2001), NeuroImage

One aspect of this study to consider is the use of laser diodes. Lasers in NIRS can be advantageous for the high intensities of light they can achieve as well as their specificity for a single wavelength, often allowing for deeper readings than LED based systems (Ferrari, 2007). Laser based systems are also often costlier and require an external control unit, limiting its portability. Another potential limiting factor is the relatively low sampling rate of 0.25 Hz used during data collection. Based on the intended goals of the study (to show differences in activation patterns in each condition), this sampling rate was adequate to achieve their goals, however, it also has implications should future researchers be interested in showing other activation characteristics such as the hemodynamic response. From this study it can be concluded that the activation of movements occurring in different limbs of the body can be monitored with enough precision to differentiate their activation patterns using high end NIRS equipment, with the limitation that only absolute activation differences were observed between tasks, with no account for the characterization of the hemodynamic profile over time.

The study by Koenraddt and colleagues (2012) made use of an 8 channel, continuous wave NIRS system with 3 cm spacing, to distinguish between neural activation being caused by rhythmic and discrete hand and foot movements. In the rhythmic condition, participants were asked to extend and flex either their wrists or ankles, following along with a visual prompt presented on screen at a rate of 0.5Hz. During the discrete condition, one of three positions were randomly presented to the participant (fully flexed, neutral, or fully extended), who held this position until the next prompt was displayed. This movement occurred at a rate of ~1 Hz. The experiment consisted of 40 trials (10 for each of the 4 movement conditions) lasting 20 seconds each, with a 20-30 seconds rest between trials. The data was analyzed using a center of gravity (CoG) approach, a technique borrowed from the field of transcranial magnetic stimulation (TMS). When applied to NIRS, this approach takes into account the amplitude of activation and the corresponding coordinates of these channels to make an estimate of one centralized location of activation. The benefit of this approach is that it allows for the analysis to determine a combined effect of activation of all channels in relation to the channel layout, which can then be compared between conditions. Results of the study showed that there was a significant medial-lateral effect of extremity, with foot movements having a CoG 0.6 cm medial to that of hand movements. These results fall in line with the expected outcome based on the lateral organization of the motor cortex. However, it should be noted the difference in upper and lower limb activation observed here is much smaller than the expected separation of 4 cm (Classen et al., 1998). This could be in part due to the limited number of channels used which potentially missed activation due to its low spatial resolution. This also may be due to the layout of

channels favouring hand related activation due to their placement covering the entire expected hand area but only partially covering the expected foot area.

No differences were observed between rhythmic and discrete tasks. The authors suggest there was a potential trend towards rhythmic tasks being more anterior, however did not achieve statistical significance. Despite this, they were still able to show activation differences along the medial-lateral axis between extremities being used. This study provides support for the use of simple hand and foot movement tasks providing enough spatial resolution to distinguish between the two major regions of activation when analyzed on a group level. However, given the smaller than expected distance between these two regions, careful consideration for source and detector placement should be taken to ensure enough of each expected motor region is being covered. This study also supports that movements, either discrete at 1 Hz or rhythmic at 0.5 Hz, are adequate to achieve observable activation.

More recently, Nishiyori and colleagues (2016) looked at improving the use of NIRS for observing activity within the motor cortex. The researchers made use of a channel configuration in which channels were aligned anterior-posteriorly, and placed side by side moving laterally (as opposed to more conventional grid shapes). The benefit of this configuration was that it would increase medial-lateral spatial resolution, however, limited anterior posterior resolution would also result. The configuration included 8 LED sources and 12 detectors. The experiment included 4 tasks: unimanual reaching right hand, unimanual reaching left hand, bimanual reaching, and stepping. The conditions consisted of 10 trials of 15 seconds, followed by 20 seconds of rest. The results of the study were able to further characterise the activation patterns associated with each form

of movement. Figure 5 shows the mean change from rest of each given channel. What can be observed is that each plot either has one peak or two peaks. Notably, what can be observed in the stepping condition is that the researchers were successful in locating a peak activation that is situated almost directly at the Cz location. This study demonstrates that for monitoring lower limb activation, channels should be situated very close or even on top the Cz location. However, it should also be noted that the results from this study may overestimate the importance of placing channels directly on top of Cz, due to a configuration that incorporated overlapping channels above Cz, thus over-emphasizing the activation occurring here. This study also supports the use of shorter task times frames, which has relevance should this be applied in clinical applications which consists of populations that may become fatigued.

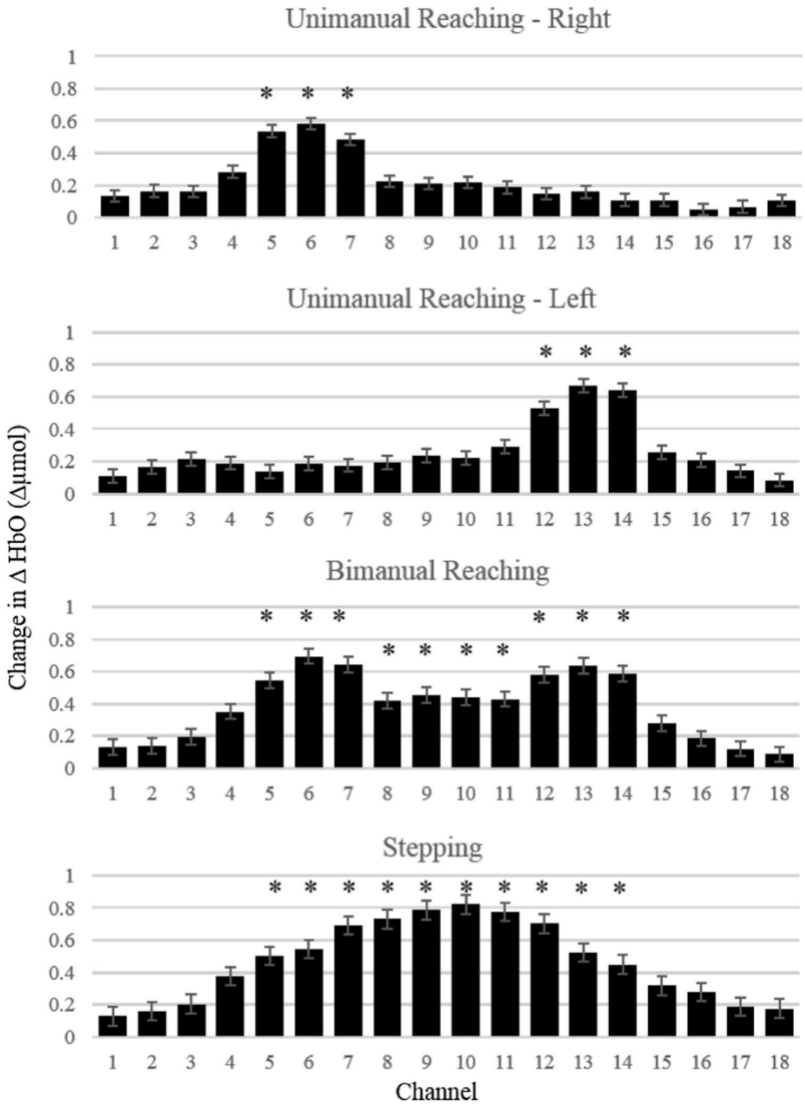

Figure 5 Mean change in HbO concentrations by task performed. Channels 8-11 are the most proximal, directly on top or near Cz. Reprinted from *Motor Cortex Activity During Functional Motor Skills: A NIRS Study* by Nishiyori et al., 2016, Brain Topography

Based on previous research monitoring neural activation arising from a motor task using NIRS, there is strong support for its use and ability to distinguish between upper and lower limb activation. Each of the above studies were able, in some capacity, to show differences between tasks being performed using upper limbs, with these actions showing more lateral activation than tasks being performed with lower limbs. However, each of

the studies intended only to show group differences, averaging the results across participants. Although this is beneficial in research to better achieve statistical significance, it does not necessarily support the use of NIRS within individuals. The use of NIRS as a stroke rehabilitation tool should also be able to demonstrate the capacity to monitor activation on an individual level, showing whether it can achieve significant results within an individual user during a single session. These studies also made use of configurations that increase the ability of the device to monitor motor regions (such as lasers or densely aligning many channels only anterior-posteriorly); however, these modifications greatly increase the cost of a given device by requiring specialized sources or an abundance of source-detector pairs. In attempts to decrease the cost of these devices, less costly and fewer components should be considered.

2.2 Axem Neurotechnology

Axem Neurotechnology is a start-up company that is working towards developing mobile NIRS technology. With technological improvements to components over the years, it has become possible to greatly reduce the size of the NIRS devices while simultaneously increasing the practicality of using the device. Axem is developing a device that interfaces directly with a computer and is self-contained to a headpiece which can be comfortably worn outside of a hospital or other clinical setting. The primary goal of Axem is to reduce the cost of NIRS devices while maintaining the quality of data being recorded from these devices, allowing it to be more accessible for rehabilitation populations.

Axem is not creating a device that is a direct replacement of a research grade NIRS. The device being designed is very specifically being used to target the motor

regions of the brain for analysis of movement related activity. Because of this, there are some limitations on what the device can do compared to a full research-grade device. For example, research-grade devices often use sources and detectors that are configurable to a given need, whereas the Axem device consists of a rigid layout which cannot be easily altered (Figure 6).

The Axem device makes use of components that are much less costly than conventional research grade NIRS devices. The benefit of doing so is that it has the potential to increase the reach of accessibility to end users (more individuals can afford the device when it is less expensive). Some preliminary work has been done within the company to validate its theoretical feasibility, however, it still requires more testing to confirm its practical use.

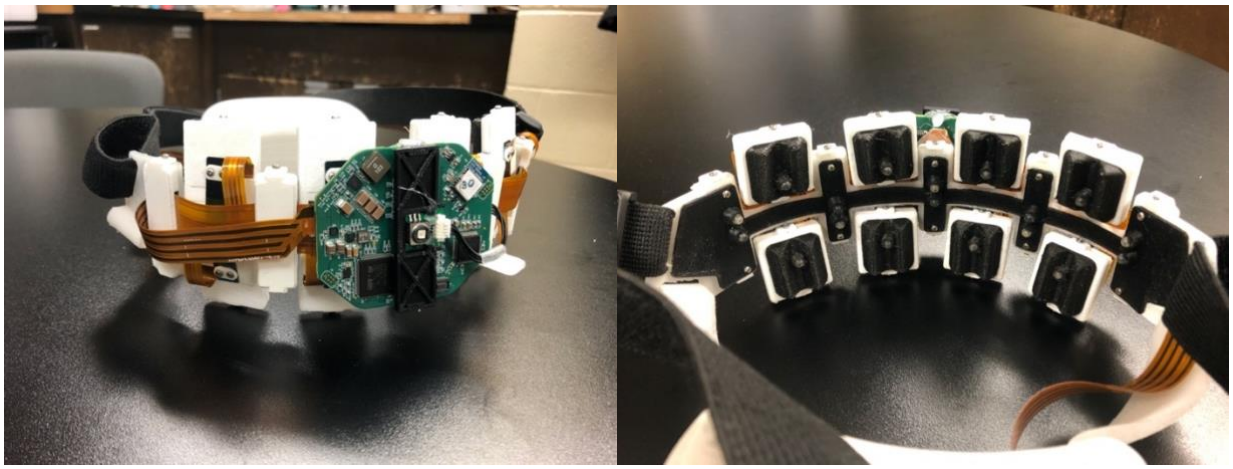

Figure 6 Mobile NIRS prototype developed by Axem Technology. Sources can be seen on the longitudinal line on the medial most aspect of the device. All other sensors are detectors.

2.4 Literature Review Conclusion

Given the principles that govern NIRS technology and the research that has already been done to support its use for monitoring neural activation in the motor cortex of the brain, there is reasonable evidence to support further exploration of its capabilities and limitations in specific use cases. Among these cases are practical applications such as its use as a tool in stroke rehabilitation. Currently, there are some limitations – such as cost, spatial resolution, and discriminating between different motor activation using minimal channels or low-cost components – that inhibit the use of NIRS on a widespread level. It stands to reason that if these limitations could be addressed and resolved, end users would benefit from an increased accessibility to such devices. End users would also benefit through a potential greater utility of the device than other more conventional devices such as EEG, which commonly have more noisy data and a greater demand on the user to operate the device (e.g. electroconductive gel).

The aim of this study is to test whether a NIRS device can be used to monitor activation in lower limb regions of the homunculus on an individual level for participants performing a single 20-minute session. The study looks to make use of a low-cost NIRS device produced by Axem Neurotechnology to assess whether the capabilities of such a device compare to that of research-grade devices.

Although direct comparisons of each component of the device cannot be performed in this case, the study aims to show significant regions of activation and how they compare between the two devices, addressing some of the benefits or drawbacks and potential causes of these discrepancies. This will include an assessment of expected number of channels becoming active during a given task, as well as the amount of activation compared to rest being achieved during these tasks.

The two purposes of this experiment will aim to asses the ability of a research grade and mobile device to monitor lower limb related neural activity through assessment of significant activation in expected locations, as well as comparing the capacity of each device to monitor signal change, specifically looking at the magnitude of change observed between rest and task. These purposes will be addresses with a specific focus on individual analysis.

CHAPTER 3 METHODS

3.1 Participants

Twenty-one healthy adults over the age of 50 were recruited, through online advertisement (Kijiji ads) and word of mouth, to participate in the experiment. Older adults were used because they reflect the typical age group of individuals post-stroke who are one of the potential clinical users of NIRS technology. Note that the planned sample was 30 participants, but due to constraints with the COVID-19 pandemic, a smaller sample is reported in this thesis. Participants were given a questionnaire to self-report possible health risks or neurological affects that could impact the outcome of the study. This list included stroke, ALS, aneurism, traumatic brain injury, and cerebral palsy (See Appendix A). If participants reported yes to any question in the questionnaire they were not recruited to participate in the experiment. Other exclusion criteria included immobility of upper and lower limbs, since this was required to perform the tasks used in the experiment. No participants reported having any of the above listed conditions. Participants were compensated $20 CAD for their participation to cover time and travel expenses. This study was approved by the Dalhousie Research Ethics Board. All participants provided informed consent before undergoing any part of this experiment.

3.2 Apparatus

Data was recorded using the NIRScout by NIRx and a prototype mobile NIRS device produced by Axem Neurotechnology. Each device used software specific to the device, along with specific equipment required for the use of each which are discussed in the following sections. Both devices were aligned using the 10/20 system (Jasper et al., 1958) for electrode placements (see Figure 7 and

Figure 8), commonly used in EEG. The NIRScout device was positioned so that detector 9 was located at Cz. The Axem device was aligned so that source 1 was directly above Cz or was 1cm anterior to Cz. Anatomical landmarks used for performing measurements were the tragus of each ear, as well as the nasion and inion, which were used to determine the midway point of each to locate Cz for a given participant.

3.2.1 NIRx Configuration

The device produced by NIRx labeled NIRScout is a variable configuration device, allowing up to 32 sources and 64 detectors that can be placed based on the desired needs of the user. For the purposes of this experiment, the device was set up with 8 LED sources, 13 Si Avalance Photodiode detectors, and 8 short-channel detectors. The montage configuration uses 3 cm spacing between adjacent sources and detectors. The NIRScout was controlled using the NIRStar program (version 15.2) developed by NIRx Medical Technologies, collecting only the raw data recorded from each channel. Data was collected at a sampling rate of 7.8 Hz. Stimuli were presented using NIRStim software presented on a 17-inch monitor. All software was run on Windows version 10. All other specifications regarding the components of the NIRScout device can be found in the NIRScout User Manual (NIRx Medical Technologies, 2013).

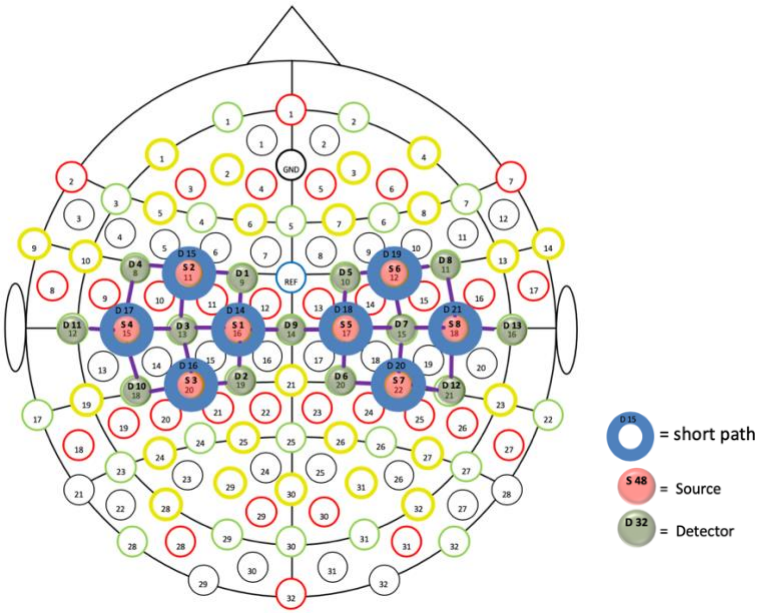

Figure 7 Montage configuration of NIRScout device

3.2.2 Axem Configuration

The prototype device created by Axem Neurotechnology is a flexible body headset comprised of 5 sources, 8 detectors, and 5 short-channel paths. The montage configuration can be found in

Figure 8. Sources used on the device were LEDs and detectors were photodiodes. It should be noted that the spacing of channels are approximately 4 cm as compared to the 3 cm spacing of the NIRScout device. The Axem headset was controlled through python-based scripts running on a Linux operating system on a MacBook Pro (2013). The headset connects wirelessly to the laptop through Bluetooth. Data collection occurred at a

sampling rate of 5.4Hz. Stimuli were presented on the 15-inch laptop display. The exact make of all of the components used in the device cannot be disclosed due to disclosure agreements with Axem Neurotechnology. For further public information regarding the device, the online resources may be referenced (axemneuro.com).

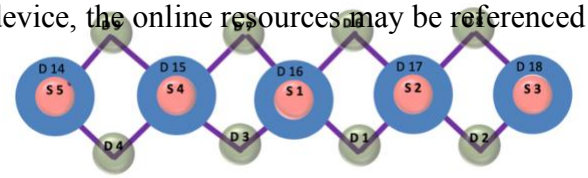

Figure 8 Montage configuration of Axem mobile device. S1 was aligned with Cz, with S3 and S5 stretching laterally across the head.

3.3 Study Design

Participants completed three blocks of trials that differed based on the device being used and its placement. One block had the participant wearing the NIRScout, while the other two were completed while wearing the Axem prototype in different locations on the head (referred to as AxemCz and AxemCa). Two different locations were used for the Axem prototype given that there is some uncertainty regarding the ideal location for the device, which also allowed for the exploration of the effect of possible inaccurate placement of the device that could arise through clinical use. The order of the devices used were pseudorandomized/counterbalanced with the stipulation that the blocks using the Axem device were consecutive which was done to reduce the amount of set up time between devices. Whether the Axem device or the NIRScout device was used first was counterbalanced, and within the two Axem blocks the order of the two possible position setups were also counterbalanced.

Within each block, the participants completed three motor tasks – right hand movement, left hand movement and marching – interspersed with rest. During a block, participants were presented with visual cues that consisted of text on screen indicating which action they were to perform (e.g. “Marching”) as well as visual cues for rest “Rest”. The task lasted for 10 seconds and was followed by 30 second rest block before the presentation of the next task. Cues appeared an equal number of times throughout the experiment and the order of presentation randomized. This randomization did allow for the same task to appear consecutively multiple times. Upon completion of any block, participants were given the opportunity to take a break if desired. It should be noted that the right- and left-hand task were included for a secondary research question and will not be used in this study.

3.4 Other Measurement Devices

During each block, heart rate, breathing, and head motion were also recorded through a Python-based script running in the background. Heart rate was monitored using an earpiece via photoplethysmography. Breathing was measured using an elastic Velcro strap fitted with stretch resistors, allowing for capture of respiratory rate and a rough estimate of depth of breath. Head motion was recorded using a 3-axis accelerometer. The placement of the accelerometer was not held entirely consistent across devices given the different physical construction of the devices. On the NIRScout it was placed on the Pz location, while on the Axem headset it was placed slightly inferior to the Oz location. These measures were collected to ensure reliability in the information being collected, allowing us to determine if excessive motion occurred that would cause motion artifacts, or whether there were large changes in heart rate or respiratory rate that may influence

the recorded data of any given participant This information was not used for any formal statistical analyses. It should be noted that although collected, this information was not used in the filtering of data for any participant included in the analysis.

3.5 Procedure

After participants provided informed consent (Appendix B), they were seated in front of the computer controlling the first device. At this time, measures of the head were taken (tragus-tragus and nasion-inion) to locate the Cz location of the head. The experimenter placed the device on the participant's head and calibration of the device was performed. Calibration was deemed to be acceptable if all channels were within the acceptable to excellent range (between 0.4 V and 4 V for the modulated raw data) (as determined by NIRStar software for the NIRScout and custom software for the Axem device, with more information at axemneuro.com). If channels were deemed acceptable or critical, they were adjusted through moving obstructions (hair) and attempting to create better contact of the source and detector to the best of the ability of the researcher and recalibrated. The experimenter then explained the tasks to the participant using the instructions in Table 1. During the rest sections the participant were instructed to sit quietly and remain as motionless as possible. The participant completed the first 20-minute block. Upon completion of the first block, participants were provided an opportunity to take a break if desired. The researcher then prepped the participant for the next block. The participant completed the second block, followed by another opportunity for a break before completing the third block. Between blocks, the experimenter set up or repositioned the device as needed according to the NIRS device condition order. Upon

completion of the experiment, participants were debriefed about the experiment and were given the opportunity to ask any further questions regarding the experiment.

Table 1 Description of motor tasks being performed during blocks

Task	Description
Right Hand	Open and close your right hand, going from fingers fully extended to making a fist, at a rate of approximately once per second for the full 10 seconds
Left Hand	Open and close your left hand, going from fingers fully extended to making a fist, at a rate of approximately once per second for the full 10 seconds
Marching	While remaining seated, raise and lower your heals off the ground, alternating feet. Participants were instructed to raise only their heels, leaving their toes on the ground at all times

3.6 Data Analysis

3.6.1 Preprocessing

For the purpose of this experiment, only hemodynamic changes related to HbO were analysed to better restrict the scope of the analysis. Many studies provide support for the use of only HbO interpretations as it usually contains larger signal changes (Koenraadt et al., 2014; Miyai et al., 2001). Of the 21 participants who participated in the experiment, one participant withdrew from the study part way through data collection and four were removed due to complications involving data collection, in which one or more conditions did not have complete data sets.

All data was preprocessed using the NirsLab software (v201904) developed by NIRx Medical Technologies. The data from all channels was visually inspected for discontinuities, artifacts, or other abnormalities. Discontinuities were corrected if consecutive points had a greater than 5 standard deviation change from the mean of all previous data points. All data following this discontinuity was corrected by subtracting a constant value of the difference of the two consecutive points from the remainder of the data. Similarly, artifacts detected as greater than 5 standard deviations were removed and replaced with the nearest signal. The exact processes for discontinuity and artifact removal can be found in the NirsLab Manual by NIRx Medical Technologies. Data was then truncated if necessary, removing sections of time not relevant to the block. The data was band-pass filtered with a low cut-off of 0.01 Hz and high cut-off of 0.2 Hz, and a roll-off width of 15%.

Hemodynamic states were then calculated using the W.B. Gratzer spectrum (W.B Gratzer, n.d.). The baseline for these calculations was the average of the signal across the entire 20-minute session. This was deemed appropriate as the analyses being performed only looked to compare a difference of activation between rest and task. At this point, all channels had the nearest short path data subtracted for the total time course. It should be noted that results obtained through the GLM did not perform this step, due to technical challenges using NirsLab. Activation patterns were averaged across trials for a given channel and visually inspected to ensure that changes in the activation were consistent with the expected hemodynamic response for an active channel (Figure 9).

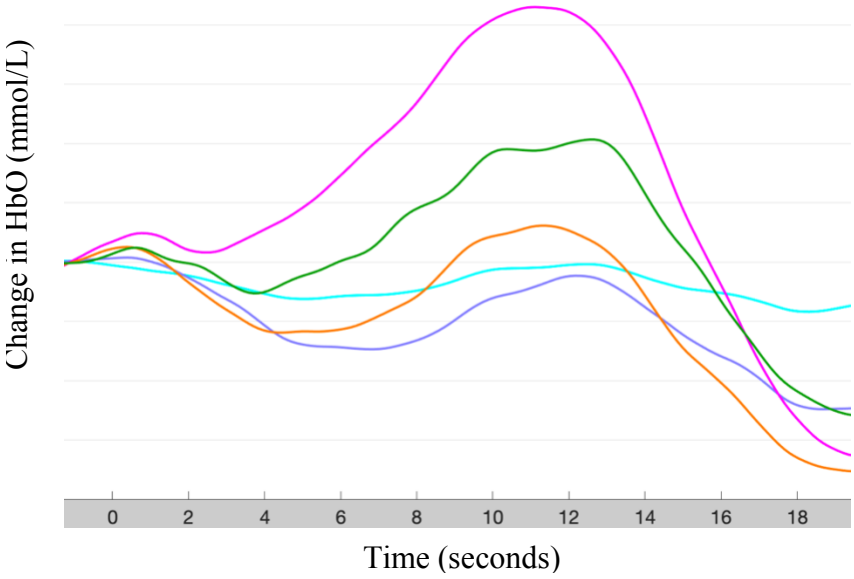

Figure 9 Example of range of hemodynamic responses that occurred at selected channels from an exemplar participant. Time point zero represents the start of a task, after which the hemodynamic response may have been positive (pink being an example of such), neutral (as seen in cyan), or possibly negative (seen in purple).

3.6.2 Regions of Interest

Regions of interest (ROIs) for this experiment were defined based on expected locations of activation related to lower limb movements. For both the NIRScout and Axem device, the most medial channels were considered to be ROIs, either directly on the medial line or 1 step removed. In the case of the NIRScout, this included 6 channels: S1-D1, S1-D2, S1-D9, S5-D5, S5-D6, S5-D9. In the case of the Axem device, this included 4 channels: S1-D1, S1-D3, S1-D6, S1-D7. Figure 10 shows a visual representation of the channel locations for each device. The goal of using a subset of these channels is to capture similar spatial regions of the head.

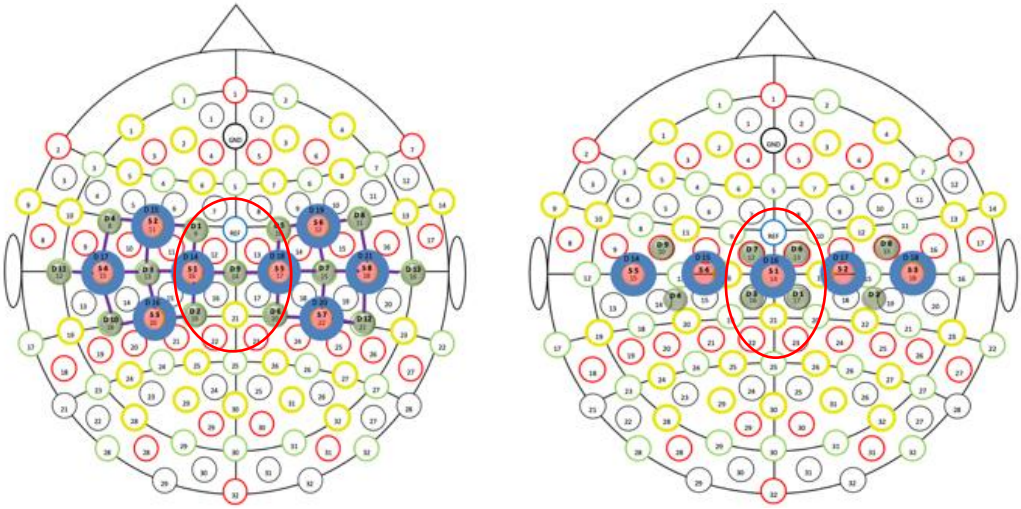

Figure 10 Channel layout of the NIRScout (left) and Axem (right) device, and the channels that are considered to be within the regions on interest. In total, the NIRScout as 6 channels within the region of interest, and the Axem has 4 channels.

3.6.3 General Linear Model

A GLM was used to analyse changes in activation associated with the marching task. The GLM made use of the Hemodynamic Response Function (HRF) as its base function with default parameters [6 16 1 1 6 0 32] to describe the function variables such as time of maximum and minimum peak (NirsLab Manual). See Table 2 for exact descriptions of each parameter. The GLM also made use of discrete cosine transform (DCT) time filtering to further reduce the effects of low frequency changes in the data to better remove any drift. The HRF function was convolved with a boxcar function representing the task and rest cycles. The left- and right-hand task was modeled for accuracy but are not reported in this document.

Table 2 Description of how each parameter effects the shape of the base HRF

Parameter	Effect on shape of function
1	Defines where the maximum peak occurs (in seconds)
2	Defines where the minimum peak occurs (in seconds)
3	Determines the dispersion of the positive-going peak
4	Determines the dispersion of the negative-going peak
5	Ratio of maximum positive value to absolute of maximum negative value
6	Lag between onset of condition and start of response (in seconds)
7	Total duration of response (in seconds)

The pre-processed data for each participant was entered into a separate GLM. The GLM produced a test statistic at each channel for each participant. Heatmaps representing the sign and magnitude of the test statistics were produced for each participant. The Benjamini Hochberg procedure was used at the participant level and set with the false discovery rate at 5% to reduce the rate of false postives. This means that there was no set value for alpha, and instead significane was based on a rank order of the test stastics, with larger test stastics being more likely to be considered significant.

To provide an overall summary across the group of which channels were significant for individual participants, the number of participants with a signficant difference at a channel was then summed for each channel. To address the first reseach question of whether NIRS could detect lower limb activity in individual participants, histograms representing the proportion of significantly active channels within each device's ROI were also produced to indicate in how many participants lower limb activity could be detected. To address the second research question of whether there was a difference between devices in detecting lower limb activation, the proportion of signiticantly active channels within the defined ROIs was calculated for each individual

for each device. A Freidman's one-way non-parametric ANOVA was performed comparing the three device conditions (NIRScout, AxemCz, AxemCa).

Finally, to determine whether devices differed in the magnitude of signal change they detected, the change in activation was calculated through subtracting the mean activation during the course of the 10 second task and subtracting it from the average activation during rest during all rest conditions throughout the block. Specifically, the rest data used was restricted to the middle 10 seconds (seconds 10 to 20 of the total 30) of the rest task to eliminate the influence of residual activation from the previous task block. The change across all marching task blocks was averaged for each participant for each device. A Freidman's one-way nonparametric ANOVA was used to compare the signal change across the three devices (NIRScout, AxemCz and AxemCa).

CHAPTER 4 RESULTS

4.1 Detecting Activation Associated with Lower Limb Movements

Average change in concentration by device was calculated using mean change in HbO calculated for each channel for each individual. Change in activation has been graphically represented through a heatmap with more positive numbers depicted in darker blue, and less positive numbers in light blue/white.

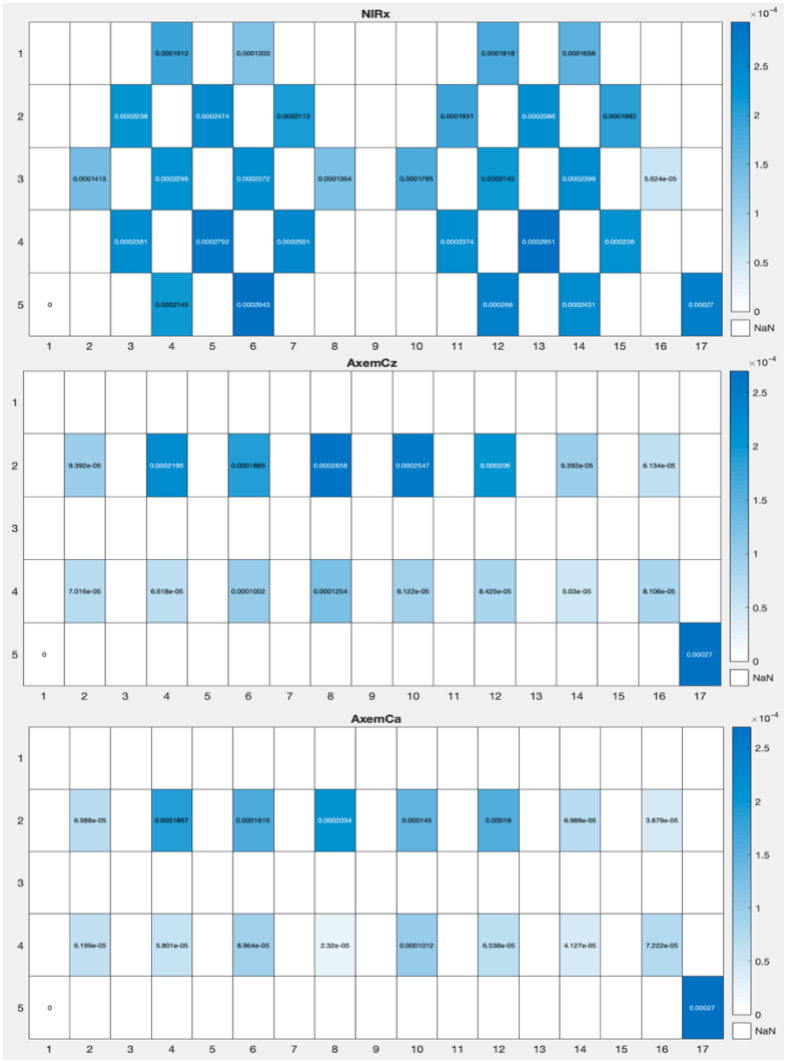

Figure 11 Average change in activation across all participants by condition (NIRScout, AxemCz, AxemCa). Note that bottom left and right corners have been used as place holders for minimum and maximum colour value, and do not represent channels.

The test statistics for each channel for an exemplar participant can be seen in Figure 12, where each cell represents a channel for that device (28 total channels for the NIRScout and 16 for the Axem device). Heatmaps for the test statistics for all participants can be found in Appendix C.

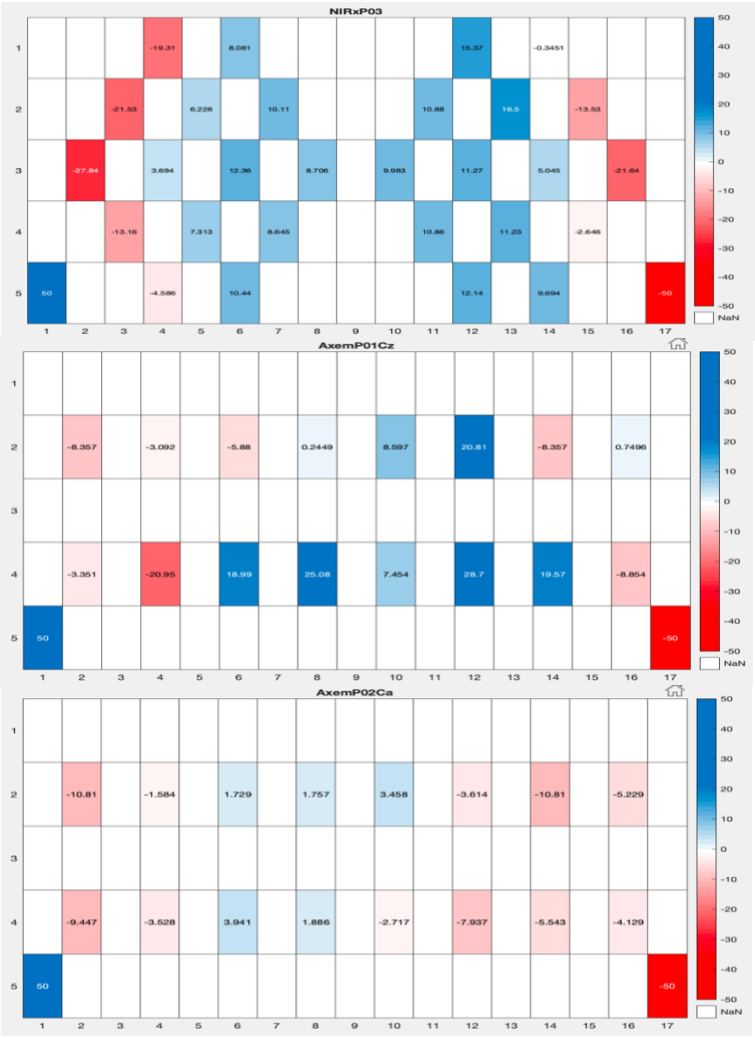

Figure 12 Example of individual heatmaps displaying test statistic for each channel optained from the GLM analysis. Channels with positive t-values are shaded in darker blue, lesser t-values in white, and negative t-values in red, allowing observation of visual trends in the significance occuring across the channels. Note that bottom left and right corners have been used as place holders for minimum and maximum colour value, and do not represent channels.

Figure 13 shows the tally of participants for each channel which had signfiicant activation following the Benjamini Hochberg correction for a given participant.

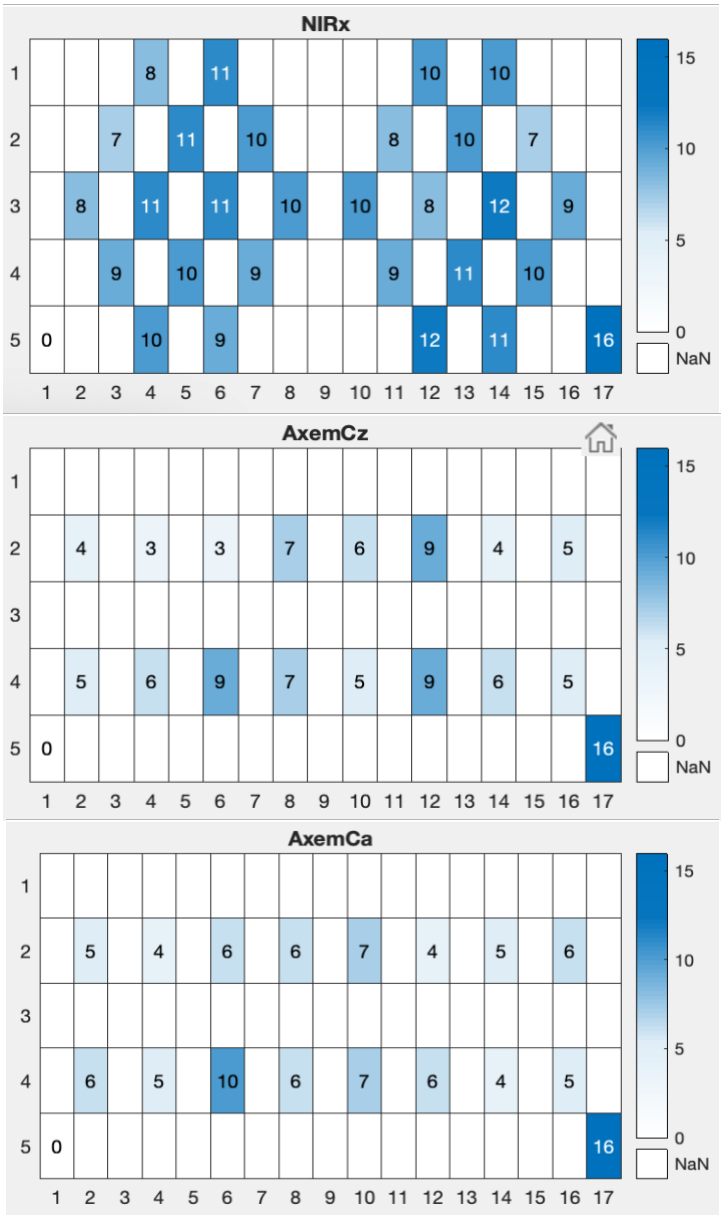

Figure 13 Heatmaps of tallies of number of individuals who were deemed to have significant activation which positively predicted changes in neural activation related to task. Note that bottom left and right corners have been used as place holders for minimum and maximum colour value, and do not represent channels.

A distribution of the proportion of significantly active channels within the ROI across participants can be seen in Figure 14. It should be noted that the bins for each device are not the same due to the difference in the number of channels within the regions of interest for each device. For the Axem device, the proportion of significantly active channels could take on the values of 0, .25, .50, .75, and 1 while for the NIRX it could take on the values of 0, .17, .33, .50, .67, .83 and 1. In the following figure, it can be observed that 3 participants in the NIRScout condition, 9 participants in the AxemCz condition, and 7 participants in the AxemCa condition showed no activation within the ROI. Turning to how many participants showed at least one channel significantly active within the ROI, in the case of the NIRScout, 81% of users had at least one channel that was determined to be significantly active, with 38% of individuals having 100% of expected channels being significantly active. In the case of the Axem, the number of users with at least 1 significantly active channel is 44% for the AxemCz condition, and 56% for the AxemCa condition. The AxemCz and AxemCa had 19% and 13% of users with 100% activation, respectively.

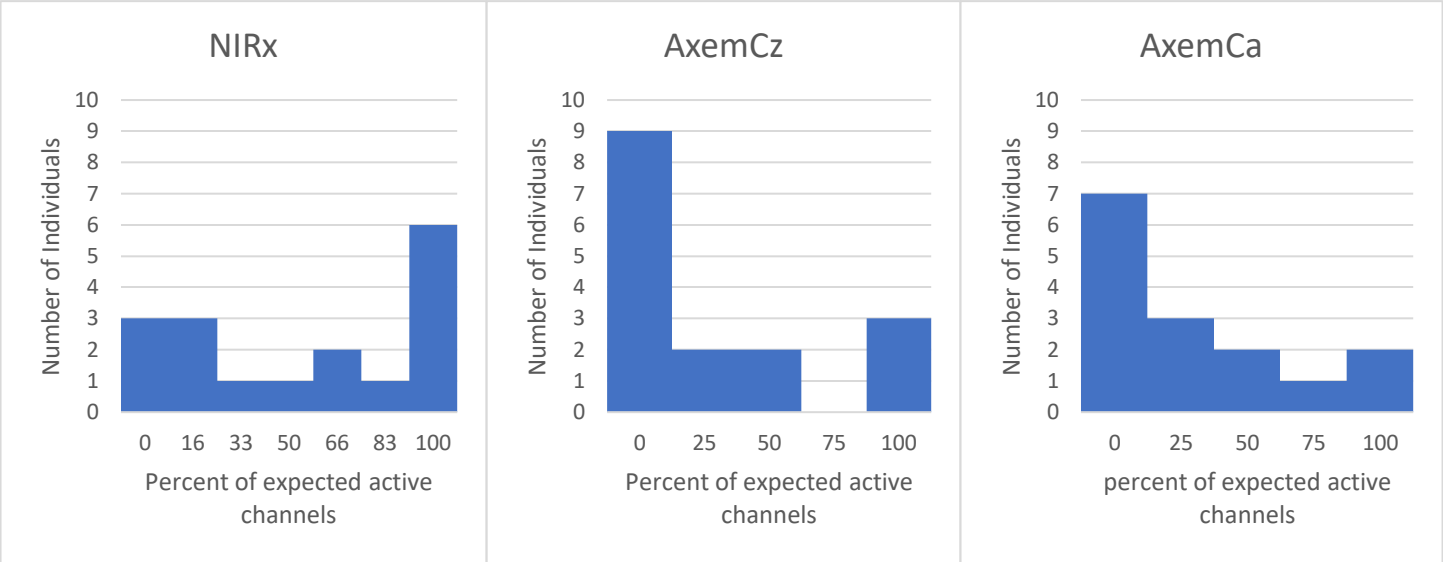

Figure 14 Histograms depicting the distribution of the percent of channels within regions of interest that were determined to be significant. (averages: NIRx = 0.55, AxemCz = 0.28, AxemCa = 0.31)

4.2 Comparing the Reseach-Grade and Mobile device

Although there appeared to be a numerical difference in the proportion of significantly active channels, there was no significant difference between the proportion of significantly active channels within the ROIs between the devices, $X_2(2) = 4.192$, $p = 0.123$.

Figure 15 depicts a line graph showing individual differences across participants by device was created to better capture some of the variability between individual users

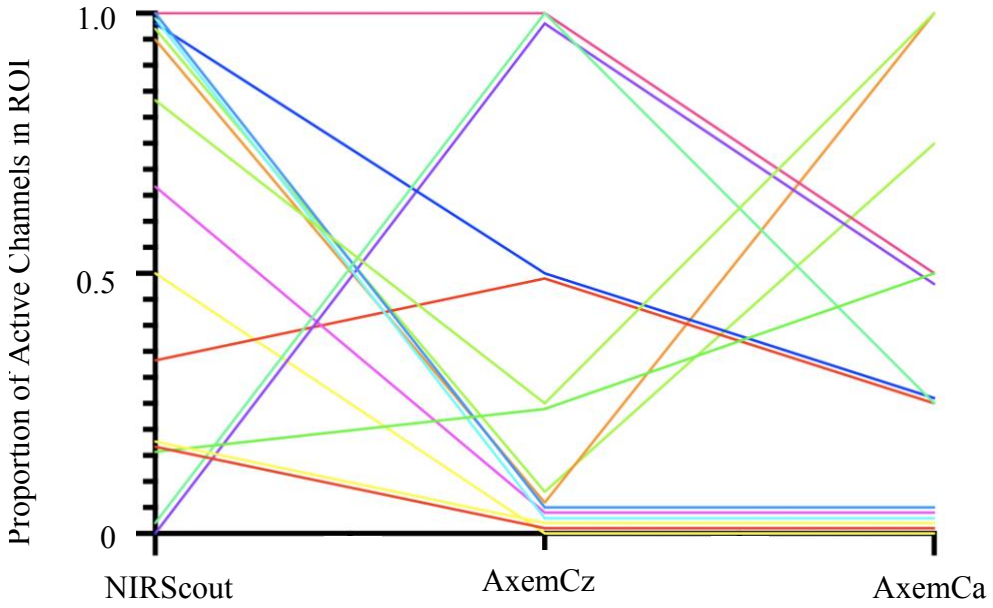

Figure 15 Line graph of percent of significantly active channels by participant per device. It should be noted that the proportions for some individuals has been jittered to manage that some participants that had similar profiles across the devices thus had overlapping lines.

A group level ANOVA comparing average change in activation between rest and task within the ROI determined that there was a significant effect of device, $X_2(2) = 6.5$, $p = 0.039$. Post hoc analysis using Mann-Whitney U test determined that the NIRScout condition was larger than both the AxemCz, $t(15)=3.26$, $p=0.0011$, and AxemCa, $t(15)=3.29$, $p=0.0009$, conditions, and there was no difference between the two Axem conditions, $t(15)=0.21$, $p=0.8337$. Individual differences have been plotted in Figure 16 to better capture the variance amongst individual users.

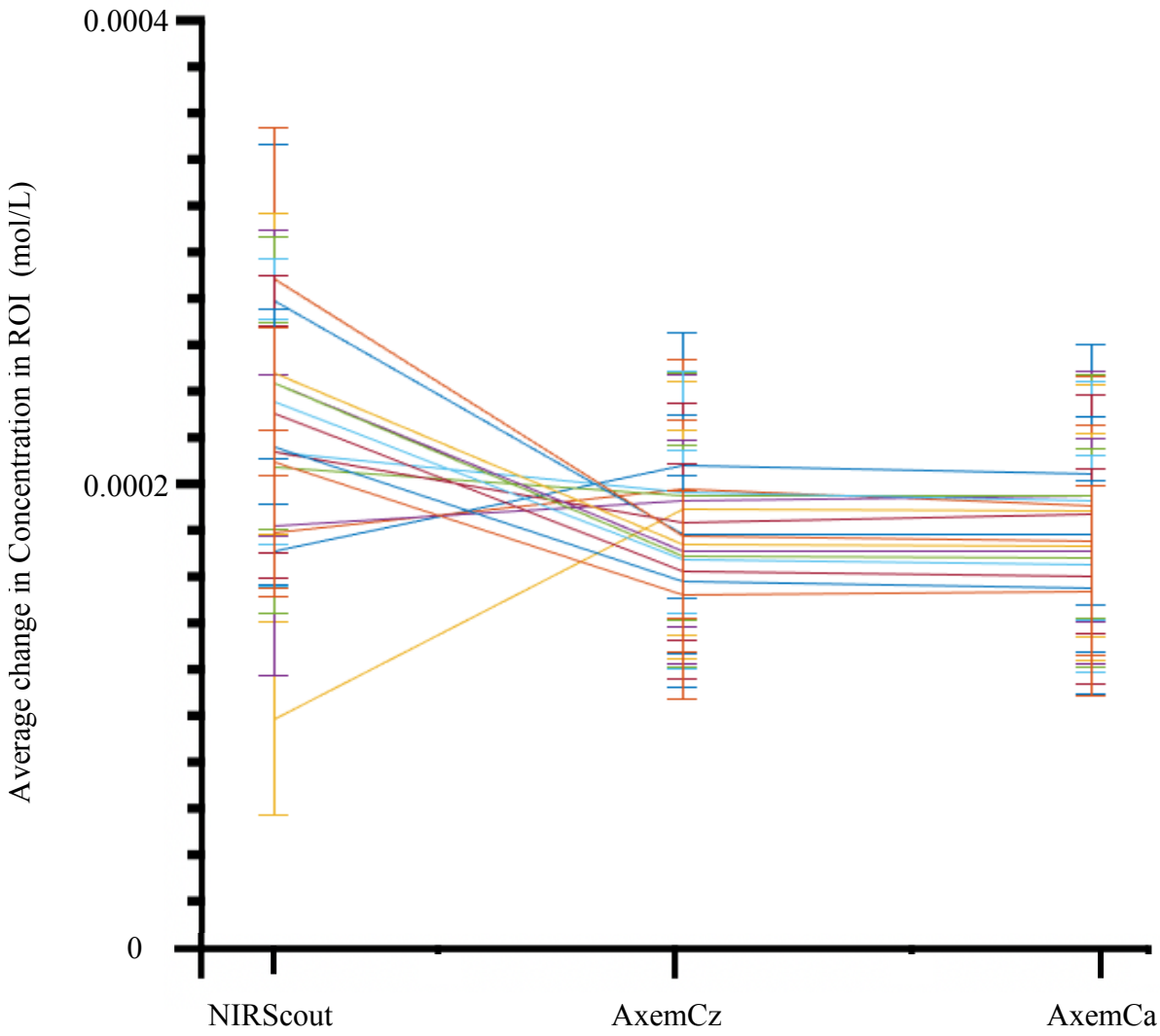

Figure 16 Average activation in ROI of individual users based on device. Lines between individual participant data points have been included so the differences across devices within and individual participant can be interpreted. Error bars represent the standard error of the mean for each participant.

CHAPTER 5 DISCUSSION

The present study had two purposes. The first purpose was to examine whether or not NIRS can be used for monitoring activation associated with lower-limb movements. The second purpose was to determine whether there are differences between the research-grade device and a mobile device to detect lower limb activity. Older adults were recruited and performed a lower limb marching task while wearing each device, with the Axem device being placed in two different locations on the head. The results associated with each purpose and the implication for mobile NIRS recording will be discussed in turn.

5. 1 Can NIRS Monitor Neural Activity Associated with Lower Limb Movements?

The first purpose examined whether changes in HbO associated with lower limb activity could be detected independently for each device. For each device, unique regions of interest were defined by selecting channels in which we would expect lower limb activity based on the layout of the motor cortex. Using a GLM, it was possible to determine the number of individuals with significant changes in HbO in the ROIs, as well as a distribution of the proportion of expected channels deemed significant for a given individual.

5.1.1 Percent of Active Channels Per Individual

All three devices were capable of observing changes in HbO concentrations associated with lower limb movements in at least some participants. The NIRScout device showed 81% of individuals with at least one significant channel, and the AxemCz

and AxemCa conditions showing 44% and 56% respectively (Figure 14). This result shows preliminary support for the ability of NIRS to monitor lower-limb motor cortex regions on an individual level. Interpreted at face value, a large portion of individuals theoretically could use either device in a single session and obtain useful information about their neural activation patterns. This does not necessarily support that NIRS can be used to measure lower limb activation for all individuals, as there would still be a large number of individuals who potentially would not observe a significant change from a given device. Working on an individual level, it would be likely that the device would be used multiple times which could affect the number of individuals who would achieve significant levels; however, future research would have to explore more of the test-retest reliability. The study by Strangman et al. (2006) suggests that NIRS has relatively strong test-retest reliability, however, makes use of longer task durations. This result also does not speak to what may be happening on an individual level, meaning it could be one of the devices that are less likely to achieve significance, or that an individual all together is not achieving any significant level regardless of device. Some of these concerns are partially addressed in later sections of the discussion.

Another consideration for the devices detecting true lower limb activity is that in the AxemCz and AxemCa data sets there is a trend towards channels within ROIs being reported as significant more frequently than channels outside this region. This pattern of activation is more in line with the expected pattern than what was observed with the NIRScout, which had similar amounts of channels outside the ROI for the lower limb being reported as significantly active as channels within the ROI. This suggests that there may be global changes occurring which are what is being detected by the NIRScout and

less so by the Axem device. Although the exact reason for why only the NIRScout would pick up this activity can only be speculated, it is within reason that either the physical components or layout of the montage could have an influence. Specifically, in the case of the Axem device, channel distances are closer to 4 cm, meaning it is possible that the Axem device is more consistently detecting activation associated only with lower limb activation because of its deeper-reaching light paths. This 4 cm spacing would also reduce SNR, because more scattering would occur.

5.1.2 Limitations Addressing Percent of Active Channels Analysis

There are a few limitations in determining whether the device was detecting true lower limb related changes. When comparing the proportion of individuals showing at least one significant channel within the ROI, the NIRScout may have had a higher probability of having at least one channel significantly active given that it had 6 possible channels within the region of interest while the Axem conditions only had 4, which could have influenced the results. Another limitation across all devices is that it is not possible to conclude whether activity being recorded is solely associated with the movements of the lower limbs. It is possible that the channels that become significantly active within the region of interest are doing so because of movements occurring elsewhere across the body. This limitation stems from the experimental design itself, in which there was little control for any other movements that participants were performing during a given task. In the case of the marching task, this could manifest itself as activation of core muscles to stabilize the individual's upper body. Although individuals were seated during the course of the experiment, if the individual had chosen to sit in a way that did not heavily make

use of the backrest, there would be a larger requirement for the individual to self-stabilize, requiring more activation of core muscle groups which could be reflected in the activity patterns observed.

It is also possible that the activity being observed may be related to global changes in activation occurring across the motor cortex. Based on previous studies using NIRS, differentiation between activation associated with upper and lower limbs can be difficult or can result in a minimal overall change in activation location. The study by Kohnraadt and colleagues (2012) showed that there was only a 0.6 cm difference between the average activation occurring during a hand movement task versus a foot movement task. Knowing that the difference can be minimal it becomes difficult to determine which aspects of the activation are directly related to only lower limb movements instead of activation that occurs regardless of the task that is being performed. One way to determine whether the activity is more reflective of the lower limb activity would be to compare the location of activation during lower limb movement and upper limb movement. Despite this limitation, it appears reasonable to assume that in part at least some activation associated with lower limb movements are being observed. Despite not being able to directly determine whether the activation is solely caused by lower limb activation, it is reasonable to assume that anyone having the intent to perform a marching task in this way would also require some form for self-stabilization, which would also be important for individuals using this device in a rehabilitation setting.

5.2 Comparing the Results Between the NIRScout and Axem Device

The second purpose was to assess the ability of each device to detect change in activation associated with lower limb activity through both an individual and group

analysis. Through comparing signal change between rest and task, as well as the percent of individuals who obtained significant activation, we can begin to draw conclusions about whether there is a benefit to using either device tested.

5.2.1 Signal Change Between Rest and Task

When examining signal change, the NIRScout device reported having on average higher levels of change in activation between rest and task. To get a better understanding of what is occurring on an individual level we can reference Figure 16 which better captures what is happening for each individual within the group. Firstly, there seems to be little to no relation between device being used and change in activation within an individual user (change in activation using one device does not predict change in activation of the other device for a given participant). It does however appear that the NIRScout often reported higher changes in activation, compared to the Axem device, as well as greater individual differences in the signal change associated with lower limb activity. This greater change in activity is in line with expected outcomes, that research-grade device would likely be more sensitive to changes than a mobile system; however, this difference is fairly minimal, with only a 0.000038 mol/L and 0.000039 mol/L change between the NIRScout and AxemCz and AxemCa condition respectively (approximately 2% of the total change in concentration). This result would indicate that there is potentially an advantage to the use of the NIRScout in terms of detecting changes in activation, however, this advantage is minimal at most, with the Axem device also capable of detecting signal change.

When it comes to interpreting this information on an individual level there are some questions of concern such as why the change in activation for the NIRScout varied so much between participants while the Axem device did not report these large differences between participants. One of the possible interpretations of this is that the Axem device may not be as sensitive to changes in activation as the NIRS device. If a device were less sensitive to change, the variance of the data would be less, thus NIRS having a larger variance could be an indication of higher sensitivity. This may be supported based on the components being used for the device as well. Given that the goal of the Axem device is to use less costly components, it is likely that the device is also less sensitive to changes in light detected. This may also be reason for the Axem device also reporting less change in activation than the NIRScout device.

5.2.2 Individuals Who Achieved Significant Activation in Expected Regions

One of the previously mentioned analyses involved assessing the proportion of channels within the ROIs that became significantly active for a given user. This information can also be used to make a comparison across devices. There was no significant difference between the proportion of significantly active channels for individuals, indicating that there was no benefit to the use of one device over the other. However, it should be noted that the result may be trending towards a difference, and it could be possible that with a larger sample size significant differences may emerge. Given the current trend in the data, if differences were to emerge, they would likely be in favor of the NIRScout device channels showing significant activation more frequently. While the NIRScout device had more channels within the ROI, possibly increasing the

probability of observing significantly active channels, the use of a false discovery rate correction within each devoice reduces this possibility.

5.3 Robustness of Axem Placement

The inclusion of multiple Axem conditions was to determine how robust the Axem device was to variation in placement given that it would be placed by users outside of the research setting. Using multiple placements also provided information on whether one placement was better than the other for recording HbO from lower limb activity. Given the results of this experiment, it would appear that the two positions performed similarly. This finding is not surprising given that difference in the placement of the device was only 1 cm, meaning any differences that would appear would be relatively small especially given the near 4cm spacing of the detectors and sources. However, given the widespread activation that was observed during the marching task, it may not be reasonable to assume that the same would apply to other tasks such as the hand tasks. An example of this can be seen in the study by Kohnraadt et al., (2012) which showed that the task being performed had a posterior-anterior effect, with rhythmic tasks being more anteriorly focused than discrete tasks. In other situations, small changes in device positioning may affect the device's ability to detect changes in activation represented by HbO.

5.4 Implications for Mobile - Clinical Use of NIRS

The results obtained from this study support the need for future research to be conducted using the Axem device, specifically with a focus for use cases within a clinical population performing neurorehabilitation tasks. The Axem device used in this

experiment showed some difference in terms of analysis outcome using the low-cost approach used to develop the device. Although the NIRScout device did out perform the Axem device in some of the measures used in this experiment, the Axem device still proved capable for a large number of individuals. Qualitatively, the Axem device was also user friendly for the researcher, and further investigations for self-use by a clinical population should be explored. Although this experiment included position variation of the Axem device, this variation was relatively controlled and thus should be explored further through more randomized placements that may occur from less experienced users.

Further future research should explore comparing task manipulations. With the focus of this analysis being primarily focused on lower limb related activity, there is little that can be concluded about how the Axem device would extrapolate to other tasks such as neurofeedback based on upper limb movements. Given that the goal of Axem neurotechnology is to apply this device in tasks that require real time feedback, further research should explore some of the limitations of processing and presenting that information to users, such as limitations on filtering, removing artifacts, and removing discontinuities.

5.5 Limitations and Future Research

One of limitations addressed during the first purpose of this experiment is that there is an inherent difficulty determining whether activation being observed is directly related to specific movements of interest. Although this study was able to show that NIRS was capable of monitoring activation represented through changes in HbO in medial regions of the motor cortex, it is not possible to definitively conclude that the activation occurring is solely related to lower limb movements. This limitation may be

more strongly routed in a limitation of the analysis having only interpreting information related to the marching task and the rest task. If the analysis had included one or both of the hand tasks, it may be possible to further differentiate activation that is unrelated or not specific to lower limb movements. The activity associated with hand movements could be compared to the activity associated with the marching task providing a set of channels that were strictly only related to lower limb movements. Other combinations of tasks could also potentially eliminate activation from other body regions such as core muscles, should the task be specific enough to not include any lower limb movements.

Another limitation that exists in the experiment involves the participant experience. Many participants reported the conditions as “boring” or “tiring”, which could lead one to presume that the participant was allowing their mind to wander during the rest or even task conditions. The result of this could mean that participants may have been either moving around during the rest task or were thinking about doing other things that may involve some kind of physical movements, or possibly missing the start of the marching task. This would result in a change in activation, and if it occurred frequently enough could influence observed results in change in activation. Noting that the intended goal of the Axem device is use for a stroke population, having the experiment being tiring and boring would also influence adherence to a given rehabilitation program, and thus should be redesigned to keep users more engaged. A possible way to mitigate this confound would be to alter the task rest cycle for longer task periods and shorter rest periods, keeping users more engaged throughout the experiment. The experiment could have also been broken into shorter blocks, allowing for more breaks to reduce fatigue throughout the experiment.

Another limitation that should be noted is that lack of use of short path removal in the GLM analysis. This limitation was largely in part due to technical limitations of analysis software used. Knowing that the use of short paths typically removes activity unrelated to the task being performed, it is likely that had short paths been accounted for, there would be an improvement in detecting changes specifically associated with the movement tasks. However, given that short paths are not strictly required to obtain results, conclusions can still be drawn from the current results.

Based on the original intended sample size of the study, there were some concerns for whether the analyses performed would have enough power. Using information from the change in activation analysis, the results were determined to have a high power (0.836).

5.6 General Conclusions

Overall there is partial support to reason the use of each device used in this experiment. The NIRScout provided evidence that it could detect larger changes in HbO, however did not show the expected trend of medial channels being more activated than lateral channels (thought should be noted this was not formally tested). The Axem device did show the expected trend for medial activation, however, showed less change in activation compared the NIRScout. As with any clinical or experimental study, the desired end goals should be weighed to optimize the desired outcomes. In the case of the Axem device, this optimization is in favor of reducing cost, allowing for robustness, and ease of use while maintaining adequate monitoring of motor regions. There appears to be a partial decrease in performance of the Axem device due to these optimizations, however they be justified due to the reduced cost. Both devices tested in this study

showed that changes in HbO in the motor cortex associated with lower limb movements could be monitored on an individual level, which supports the potential use within individual users as a possible rehabilitation tool. This study was also able to show minor differences between the Axem device and NIRScout device, and these differnces should be considered heavily for future advancements of mobile NIRS technology, to ensure maximum performance while reducing overall cost.

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APPENDIX A

History with Neurological Affliction

Please specify whether you have ever experienced the following afflictions. When responding YES please indicate when you experienced this or were diagnosed.

YES NO

____ ____ ***Stroke*** If yes, when?
_____

____ ____ ***Aneurism*** If yes, when?
_____

____ ____ ***Traumatic Brain Injury*** If yes, when?
_____

____ ____ ***ALS*** If yes, when?
_____

____ ____ ***Cerebral Palsy*** If yes, when?
_____

APPENDIX B

CONSENT FORM

Project title: Comparison of two devices' ability to measure movement-related brain activity

Lead researcher:
Dr. H.F. Neyedli
Assistant Professor
School of Health and Human Performance
Dalhousie University
(902) 494-6786

Other researchers

C. Friesen
PhD Candidate, Co-Founder of Axem Neurotechnology Inc.
Department of Psychology/Neuroscience
Dalhousie University
(902) 880-8004

C. Hollands
MSc. Student
School of Health and Human Performance
Dalhousie University

Introduction

You have been invited to take part in a research study. A research study is a way of gathering information on a treatment, procedure or medical device or to answer a question about something that is not well understood. Taking part in this study is voluntary. It is up to you to decide whether to be in the study or not. Before you decide, you need to understand what the study is for, what risks you might take and what benefits you might receive. This consent form explains the study.

Please read this carefully. Take as much time as you like. If you like, take it home to think about it for a while. Mark anything you don't understand, or want explained better. After you have read it, please ask questions about anything that is not clear.

The researchers will:

- Discuss the study with you
- Answer your questions
- Keep confidential any information which could identify you personally

Be available during the study to deal with problems and answer questions

Purpose and Outline of the Research Study

When you move your body, several brain areas become active as commands are sent from your brain to your body. This study's purpose is to examine the ability of two devices to measure this response in individuals over the age of 50.

Axem Neurotechnology, a company co-founded by one of the investigators, is developing a product being designed to provide information from the brain to healthcare professionals during physical rehabilitation following stroke. The purpose of this research study is to determine whether their current prototype can measure movement-related brain activity in representative users as well as a more established device which uses the same technology.

Conflict of Interest

One of the 'other researchers' listed (C. Friesen) is a co-founder and stockholders in Axem Neurotechnology, the company that is designing and manufacturing one of the devices being used to measure brain activity in this study. Christopher Friesen could benefit financially from the outcome of this study; in order to ensure this does not affect the integrity of the study results, both the lead researcher supervising all aspects of the study (H. Neyedli) as well as the researcher conducting and overseeing the data collection (C. Hollands) are not a stockholders in the company.

Who Can Take Part in the Research Study

You may participate in this study if you are 50 years of age or older.

What You Will Be Asked to Do

In this study, you will first fill out two self-report questionnaire asking you for some basic demographic information, as well as asking you questions about which hand you would use for various tasks (to assess how left- or right-handed you are).

During the remainder of the study you will be asked to perform two simple movement tasks. The first movement task will require you to put your fingers through the holsters of a small, soft exercise ball, and to squeeze either your left or right hand (approximately once per second) when instructed. The second movement task will ask you to march on the spot (at a typical walking speed) while seated.

You will be asked to perform these two movement tasks under three conditions: in two separate conditions while the Axem Pro measures your brain activity (each time the device will be positioned in a different location), and once while your brain activity is being measured using an established research system. Each condition will last 26 minutes. **The entire study will last a maximum of 2 hours.**

Demographic information

We will ask you your age, as well as whether you have been diagnosed with any musculoskeletal afflictions (e.g., ALS or cerebral palsy).

History with Neurological Afflictions Questionnaire

We will ask you to indicate whether you have expected select neurological afflictions, and to provide information on when you have experienced them if so. Having experienced any of these afflictions does not affect your ability to participate in this study.

Handedness Questionnaire

This questionnaire will measure how right-handed or left-handed you are. We will ask you to complete this questionnaire at the beginning of the study session. To complete this questionnaire, you will be given a list of ten every-day, common, one-handed tasks. You will be asked which hand you use to perform these tasks. This information will allow us to determine whether you are right or left-handed.

Brain activity
Activity in your brain will be measured using two functional near-infrared spectroscopy (fNIRS) devices. fNIRS measures blood flow in the brain, which relates to brain activity. The Axem Pro device is a wireless headband, held in place by straps which also house its battery. The NIRscout device measures from a larger area of your brain, and fits onto your head with an elastic headcap.

Exercise Ball Squeezing Task

This task will be performed seated, and will require you to put your fingers through the holsters attached to a small, soft exercise ball. When you hear the word 'left', you must squeeze the ball in your left hand. Try to squeeze the ball approximately once per second, and use a moderate amount of force—enough so that the ball deforms in your hand, but not so much that you feel muscle strain or fatigue. Likewise, when you hear 'right' you will squeeze the right hand in the same way. And finally, when you hear 'rest', you can simple put your hands in your lap and relax waiting for the next instruction. Hand squeezing blocks will last 10 seconds, while rest blocks will last 30 seconds.

Seated march Task

The task will require you to march in place (at a regular walking speed) when you hear the word 'march'. When you hear the word 'rest' you can stop marching and rest. You will be seated throughout this task, with your hands in your lap. Marching blocks will last 20 seconds, while rest blocks will last 30 seconds.

Pain/Comfort Feedback

Following each condition, the experimenter will ask you a simple question about the level of pain/comfort you experienced during that condition—rating on a scale of 1-10, with 1 being no pain/discomfort at all, 3 being moderately uncomfortable, 5 being quite uncomfortable or

slightly painful, 7 being moderately painful, and 10 being almost too painful to continue. The possibility that you may feel pain or discomfort is not related to the shining of non-ionizing infrared light, but rather only related to the fit of the head mounted device against your head.

It is important for you to remember that if you do feel pain and/or discomfort such that you would like to stop the experiment, please do not hesitate to let the experimenter know and it will stop immediately.

Possible Benefits, Risks and Discomforts

Benefits

There will be no direct benefits for participating; however this study has the potential to contribute to the creation of a product that could improve physical therapy outcomes for stroke patients and/or make high-quality therapy more accessible by reducing its cost.

Risks
The risks associated with this study are minimal; you may become bored or fatigued from participating in this research. However, there will be several minutes of rest between conditions as the experimenters set up the next condition; and moreover, **you may ask for more time between conditions or between tasks if you are feeling fatigued**.

There is minimal risk related to the use of fNIRS, including the potential for discomfort from the straps and/or headband/headcap. The fNIRS device emits light in order to measure blood flow in the brain, and the power at which it emits light are within those specified by the International Electrotechnical Commission not to cause harm.

Compensation / Reimbursement
You will receive $20 to compensate you for your time and for any other expenses you may have incurred as a result of participating in this study (e.g., parking). You will receive compensation even if you choose not to continue once you have started the session.

How your information will be protected:
Privacy: Protecting your privacy is an important part of this study. Every effort to protect your privacy will be made. No identifying information (such as your name) will be sent outside of Dalhousie University. If the results of this study are presented to the public, nobody will be able to tell that you were in the study.
If you decide to participate in this study, the research team will look at your personal information and collect only the information they need for this study, such as your;

- Name
- Age
- Information from the study questionnaires

Confidentiality: In order to protect your privacy and keep your participation in the study confidential, you will be de-identified using a study code. For the purpose of data analyses, all participants will only be identified by their study code (e.g. s001). All hard copy data associated with the study (including this consent form) will be stored in a locked filing cabinet in a secured laboratory that is accessible only to lab personnel and who are trained in confidentiality. All

electronic data will be de-identified (i.e., will not contain identifying information about you, such as your name and age), and this data will be stored both on (1) a secure, password-protected server in the Cognitive and Motor Performance Lab, as well as (2) on a third-party data hosting service maintained by Axem Neurotechnology; these data (in compliance with Federal and Provincial data privacy legislation) will first be encrypted using an industry-standard cipher (ex. AES-256) and a unique strong password generated and managed by a secure password management system (e.g., lastpass). No documentation will exist (hard copy or electronic) that links your name with your study code.

Data retention: Information that you provide to us will be kept private. We may describe and share our findings in theses, presentations, public media, journal articles, etc. We will be very careful to only talk about group results so that no one will be identified. This means that ***you will not be identified in any way in our reports***. The people who work with us have an obligation to keep all research information private. Also, we will use a participant number (not your name) in our written and computer records so that the information we have about you contains no names. All your identifying information will be securely stored. All electronic records will be kept secure, password protected server in the Cognitive and Motor Performance Lab.

If You Decide to Stop Participating
You may choose not to continue your participation in the study at any time. You will still be compensated for your time (i.e., with $20) if you choose to withdraw before the study's completion. You may also withdraw your data for up to one week after participation. After that, your data will be integrated in our data analysis therefore we cannot withdraw it.

How to Obtain Results
If you would like to receive a notification about the publication of the data from this study in a peer-reviewed journal, provide your email address where specified on the bottom of this consent form.

Questions
We are happy to talk with you about any questions or concerns you may have about your participation in this research study. For further information about the study you may call the principal investigator, who is the person in charge of this study.

The principal investigator is Dr. Heather Neyedli
Telephone: (902) 494-6786s
We will also tell you if any new information comes up that could affect your decision to participate.

If you have any ethical concerns about your participation in this research, you may also contact Research Ethics, Dalhousie University at (902) 494-1462, or email: ethics@dal.ca

In the next part you will be asked if you agree (consent) to join this study. If the answer is "yes", you will need to sign the form.

Signature Page

Project Title: Comparison of two devices' ability to measure movement-related brain activity

Lead Researcher:
Dr. H.F. Neyedli
Assistant Professor
School of Health and Human Performance
Dalhousie University
(902) 494-6786

I have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction.

I understand that I have been asked to take part in a single session and I agree to take part in this study.

I agree that my study information may be used as described in this consent form.
My participation is voluntary and I understand that I am free to withdraw from the study at any time throughout the session.

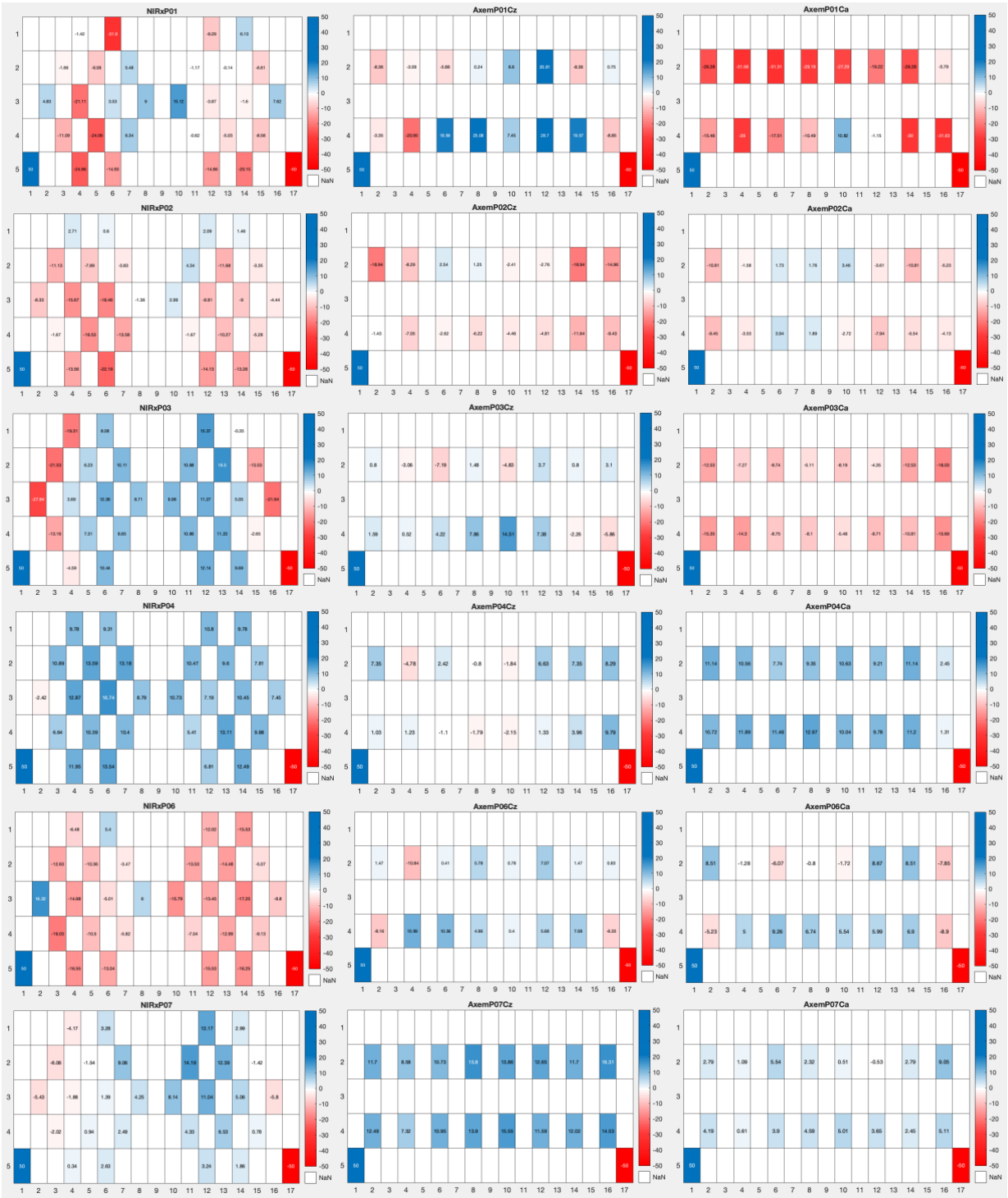
_____	_____	_____
Name	Signature	Date

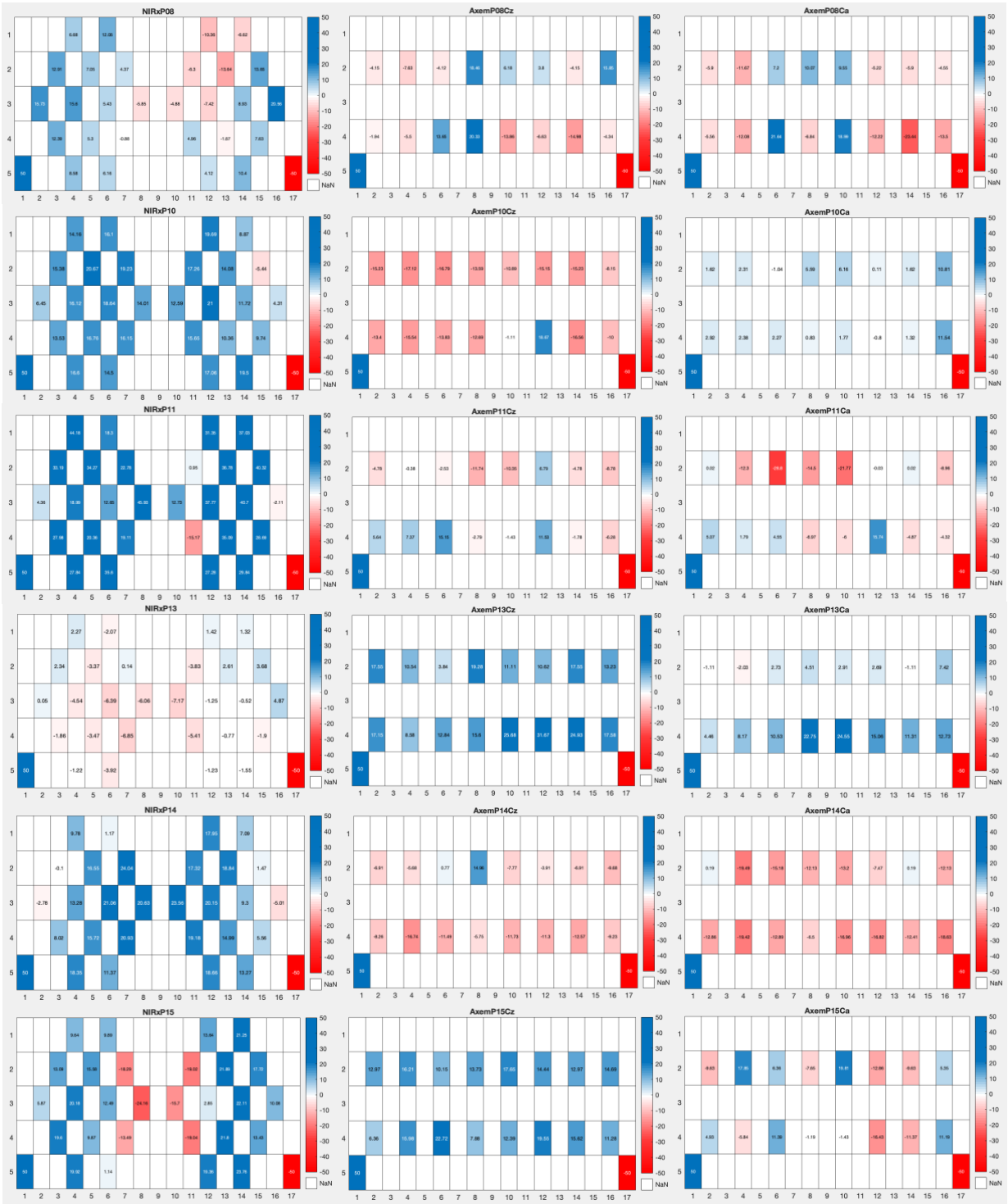
If you would like to receive a summary of the data from this study upon completion, provide your email address below:

_____

APPENDIX C

Independent heatmaps depicting test statistic results obtained from GLM analysis

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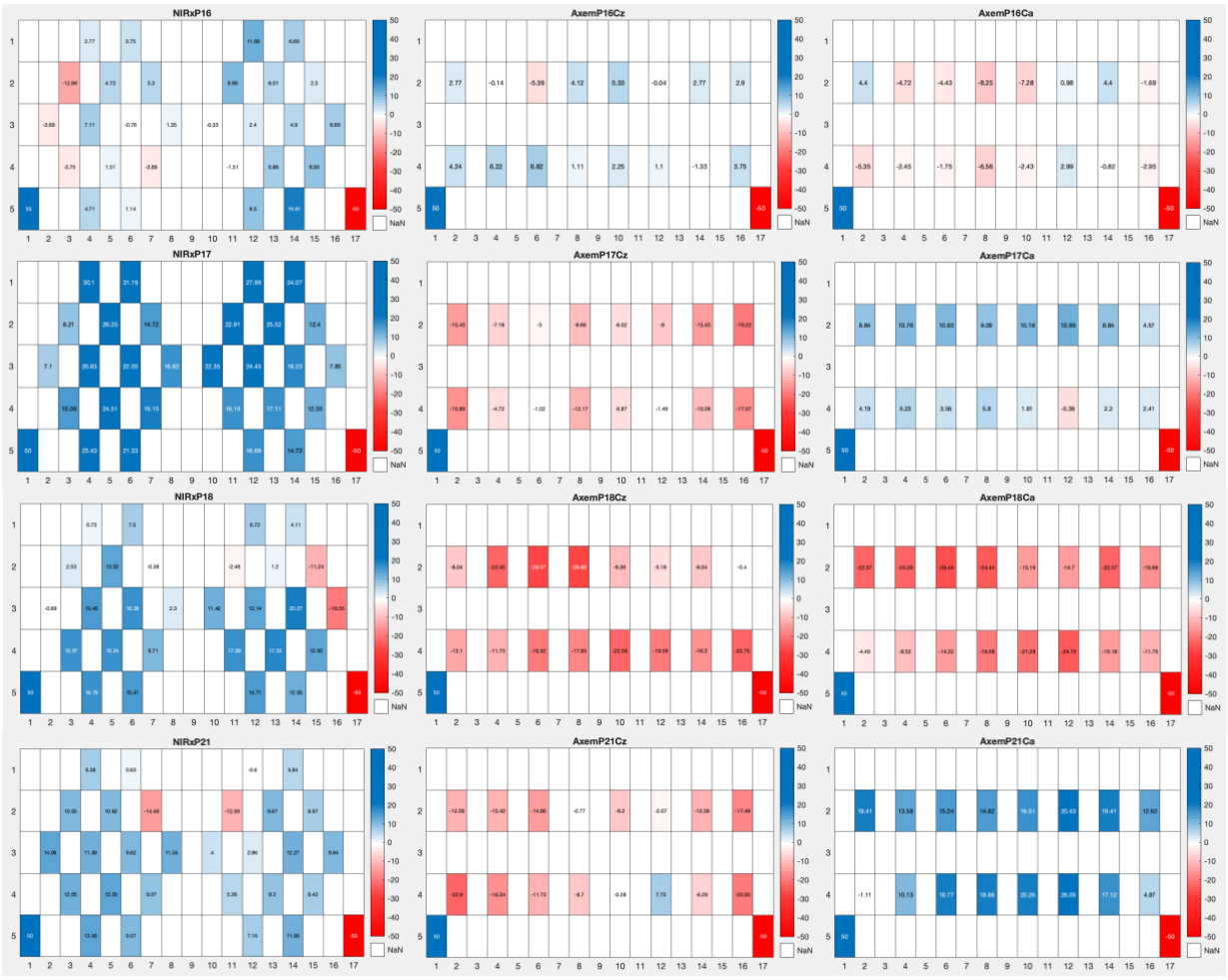
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