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Measuring the Effects of Sport-Related Concussion on Default Mode Network Activity Using Functional Near Infrared Spectroscopy

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Measuring the Effects of Sport-Related Concussion on Default Mode Network Activity Using Functional Near Infrared Spectroscopy

By

Brian Taylor

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Submitted to the Faculty of Graduate Studies
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Measuring the Effects of Sport-Related Concussion on Default Mode Network
Activity Using Functional Near Infrared Spectroscopy

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ABSTRACT

Sport-related concussion is a serious and frequently occurring health condition that impacts the lives of athletes. It is important to correctly diagnose concussions in athletes to avoid potential further injury. However, concussions are difficult to diagnose because there are currently no medical tests to identify them. Neuroimaging may be a useful technique in diagnosing concussion and understanding the neuropathological mechanisms of concussion sequalae. The default mode network is a neural network associated with processes such as episodic memory and self-reflection. It is active when a person is at rest and is not focused on completing a task, Research suggests that sport-related concussion can negatively impact the activity of this neural network. This study analyzed default mode network activity in male and female varsity athletes with a sport related concussion (Mean age = 21.33, SD = 0.577; 2/3 female) and healthy male and female control individuals without a sport-related concussion (Mean age = 21, SD = 2.64; 9/15 female) as well as healthy control varsity athletes without a sport-related concussion (Mean age = 22, SD = 0; 2/2 female). All individuals completed a stop-signal task that acted as an active trial and a rest trial where their default mode network activity was recorded with fNIRS. Concussed female athletes showed lower levels of default mode network activity than control females during rest tasks. Concussed female athletes also showed lower levels of default mode network activity compared to control females and control female athletes during active tasks. This suggests that concussed females showed abnormal activity in default mode network associated regions compared to healthy controls especially when switching between active and rest trials. Increased activity in default mode network regions was observed between control athletes and control non-athletes during rest tasks, suggesting that an active lifestyle may affect default mode network activity in healthy individuals. Overall, the results of this pilot study suggest that fNIRS is useful for identifying concussion and that it may help to explain observed sex and gender differences in sport-related concussion.

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CHAPTER 1

Introduction

Mild Traumatic Brain Injury

Traumatic brain injury (TBI) is a serious health issue worldwide, with an estimated 69 million events occurring every year (Thurman, Alverson, Dunn, Guerrero, & Sniezek, 1999; Dewan et al., 2018). Over 10 million events of TBI result in hospitalization or death annually (Langlois & Wald, 2006). Older adolescents aged 15 to 19 and older adults aged 75 and above are the most likely age groups to suffer TBI (Langlois & Wald, 2006). The majority of traumatic brain injuries are classified as mild traumatic brain injuries (mTBI), more commonly referred to as concussions (Thurman et al., 1999; Cassidy et al., 2004; Langlois & Wald, 2006).

Mild traumatic brain injury is caused by an external force being applied to the head or body resulting in a change of cognitive state (Cassidy et al., 2004; Ruff et al., 2009). Many individuals experience the symptoms and effects of mTBI differently, making diagnosis and treatment of this condition challenging. As there is currently no universal method for diagnosis of a mild traumatic brain injury a more individualistic approach is often taken, typically relying upon self-reported changes in the individual's cognitive state following the injury as well as common symptoms that may occur following concussion (Scorza & Cole, 2019).

The changes in cognitive state that are often viewed as signs of concussion following an injury to the head involve loss of consciousness, memory issues, or confusion shortly after the injury (Cassidy et al., 2004; Ruff et al., 2009; Scorza & Cole, 2019). The guidelines set out for the diagnosis for mTBI as stated by the American Congress of Rehabilitation Medicine require a traumatically induced physiological disruption of brain function which is exhibited through either a loss of consciousness of less than 30 minutes, a loss of memory pre- or post-injury for a

period less than 24 hours or a change in mental state such as feeling dazed, disoriented or confused (Ruff et al., 2009).

The most common symptoms of concussion include nausea, headaches, dizziness, sleep disruptions, irritability, problems with attention, and difficulty paying attention or focusing on a task (Prince & Bruhns, 2017; Scorza & Cole, 2019). These symptoms are observed in individuals who have sustained a concussion ranging from various causes such as motor vehicle accidents, falls, and sports (Scorza & Cole, 2019).

Sport-Related Concussion

Sport-related concussion is a common form of mild traumatic brain injury and is most prevalent in adolescents and young adults (Cassidy et al., 2004). This is especially true in the case of high school and university level sports where sport-related concussion occurs at its highest rate (Meehan & Bachur, 2009). Although concussion can occur in any sport, sports that involve regular physical contact such as football, hockey, and lacrosse put athletes at the greatest risk of concussion. (Daneshvar, Nowinski, McKee, & Cantu, 2011).

There are over 8 million athletes involved in sports at the high school and collegiate level annually in the United States (Kroshus et al., 2016). Of these sports American football makes up approximately one third of the total sports played at the high school level and over one third of total sport involvement at the collegiate level (Daneshvar et al., 2011). It is estimated among these football players, the annual rate of concussion will be 4 out of every 100 players (Daneshvar et al., 2011).

Even though concussion is a common injury in sport, the actual number of concussions reported is drastically lower than the number sustained by athletes (Meehan & Bachur, 2009; Erdal, 2012; Kroshus et al., 2016). It has been reported that over one third of athletes do not

recognize their concussion symptoms and only 19% of professional football players in the Canadian football league knew that they had sustained a concussion from an injury (Meehan & Bachur, 2009). Even when the effects of their injury are severe and involve loss of consciousness, athletes often still do not recognize this as a sign of concussion (Meehan & Bachur, 2009). A study of high school football players in Minnesota found that 69% of players who experienced a loss of consciousness following an injury during play returned to play during the same day (Meehan & Bachur, 2009). Even as understanding and regulations regarding concussion have increased in recent years, a 2020 study of high school soccer players, found that 40% of these athletes still returned to play the same day that they had sustained a concussion (Zynda et al., 2020).

Underreporting of concussion is often due to the athlete not recognizing that they have even sustained an injury, however, sometimes athletes purposely avoid reporting a concussion to avoid being removed from play (Meehan & Bachur, 2009; Erdal, 2012; Asken et al., 2016; Kroshus et al., 2016). Athletes at a collegiate or professional level are under a lot of pressure to perform at high levels and they view being removed from play for a concussion could negatively impact their sporting career and in some cases livelihood (Kroshus et al., 2014 Kroshus et al., 2016). High school athletes face pressure to avoid reporting concussions because being removed for a few weeks or even a season could negatively impact their chances of receiving sports scholarships or acceptance into college/university programs (Kroshus et al., 2016).

A technique that is sometimes utilized by athletes to avoid having their concussion detected is called sandbagging (Erdal, 2012). Sandbagging refers to when an athlete purposely underperforms in baseline cognitive testing at the beginning of the season so that if they ever sustain a concussion or injury that interferes with their cognitive ability, their performance will

appear normal on cognitive testing following the injury due to the poor preinjury baseline they produced (Edal, 2012). This creates the impression that there are not significant differences in their cognitive functioning following the injury and reduces the chance that their concussion will be detected allowing them to return more easily to play even if they have sustained a concussion (Erdal, 2012).

Pressure can even be placed on athletes to not report a concussion from other members of their team, coaches, and even fans of the sport (Baugh et al., 2014; Kroshus et al., 2016). Around 25% of athletes report that they have felt pressure from a coach teammate, or fan to return to play following a head impact or potential head injury during the sporting season (Kroshus et al., 2016). Athletes that faced pressure to return to play following a head impact or felt pressured to not report a concussion were also more likely to not report future concussions as well which could lead to an increased risk of future injury and possible long-term consequences on the athlete's health (Guskiewicz, Ross, & Marshall, 2001; Guskiewicz & Broglio, 2015; Kroshus et al., 2016).

Typically, the symptoms of a concussion usually last two to three weeks following injury (Eisenberg, Meehan, & Mannix, 2014). This two to three-week period where people experience symptoms such as nausea, trouble sleeping, and irritability is called the acute stage of concussion (Guskiewicz et al., 2001). Although these symptoms typically resolve after a few weeks, a minority of people report headaches and taking longer to think and complete cognitive tasks months after their injury (Eisenburg et at., 2014).

Some research suggests that between 20 and 30% of people report post-concussive symptoms up to three months following injury (Eisenburg et al., 2014; Quinn et al., 2017). However, it is difficult to trace the origin of the symptoms an individual is experiencing as many

post-concussive symptoms are also regularly observed in healthy individuals such as nausea, dizziness, and headaches (Rohling et al., 2011). Other clinical conditions such as learning disabilities that are unrelated to concussion may also lead to increased rates of symptoms erroneously being attributed to the concussion (Rohling et al., 2011).

Repetitive concussions can lead to possible long-term physical and cognitive deficits in athletes (Rabadi & Jordan, 2001; Zemper, 2003; Nordström, Nordström, & Ekstrand, 2014; McAllister & McCrea, 2017). Repetitive concussions could increase the vulnerability of individuals to psychiatric disorders, sleep difficulties, sadness, and anxiety (McAllister & McCrea, 2017). Alongside the increased risk of these cognitive disorders, physical differences in balance and a person's natural gait have also been found in individuals who have sustained multiple concussions throughout their lifetime (Guskiewicz et al., 2001).

This is especially concerning given that individuals that have sustained one concussion are at a much greater risk of a subsequent concussion in the future (Zemper, 2003; Nordström, Nordström, & Ekstrand, 2014). In a study of 46 professional male soccer players, Nordström et al., (2014) found that athletes who had sustained a concussion were 50% more likely to sustain another concussion or injury in the following year than those who were not concussed. Athletes with a history of concussion have also been found to have a 5.8 times greater chance of receiving a subsequent concussion throughout their athletic career than those without a history of past concussions (Zemper, 2003).

Sex/Gender Differences in Concussion

The effects of sport-related concussion on athletes are still not entirely understood. Current research into sport-related concussion, indicates that there are sex/gender differences between male and female athletes when looking at the effect of concussion on specific brain

regions and recovery (Covassin et al., 2003, 2006, 2007, 2012; Broshek et al., 2005).

Differences in baseline neuropsychological testing performance between males and females has

also been observed (Covassin et al., 2006).

In a 2005 study, following a sport-related concussion, female athletes were consistently

more likely to show declines in cognitive functioning as well as demonstrate more concussive

symptoms than concussed male athletes (Broshek et al., 2005). Similarly, differences in

emotional processing post-injury have also been observed (Covassin et al., 2007). Males were

more likely to report symptoms such as sadness than females (Covassin et al., 2007). Often,

sport-related concussion research does not address these specific sex/gender differences when

looking into the effects of concussion on athletes limiting the ways treatment and understanding

of these injuries can be further explored.

Females are also more susceptible to concussions following a head injury than males and

some sports such as female ice hockey over 18% of total injuries reported are concussions

compared to male ice hockey in which concussion only makes up a total of 8% of injuries

sustained (Daneshvar et al., 2011; Mollayeva et al., 2018; McGroarty et al., 2020). Some

possible explanations for the increased vulnerability of females to concussion could be

associated with hormonal differences and the higher levels of estrogen and progesterone in

females compared to males as well as the outcome of concussion possibly being influenced by

menstrual cycle phases (Covassin & Elbin, 2011).

Research into gender norms and symptom reporting also suggest that it might be more

likely that females will report more symptoms and a higher severity of the symptoms than males

even if the males are experiencing the same symptoms (Covassin & Elbin, 2011). The

underreporting of symptoms and symptom severity in male athletes especially in traditionally

masculine and highly physical sports such as football or hockey due to pressure to avoid being perceived as weak (Covassin & Elbin, 2011).

Anatomical differences and differences in size between males and females could also contribute to differences in the rate of concussion (Tierney et al., 2005; Vasavada, Danaraj, & Siegmund, 2008). Females typically have a smaller head mass as well as a shorter and narrower neck compared to males which could result in greater head acceleration following an impact resulting in an increased risk of concussion or head injury (Tierney et al., 2005; Vasavada et al., 2008).

Even though there is some research targeted at gender/sex differences in concussion, the growing body of literature stresses the importance of taking these differences into consideration to better understand the effects of concussion symptoms, reporting, and plans for treatment and recovery.

Neuropathological Changes in Concussion

Given the complexity of concussion diagnosis and lack of medical tests, there is a need to establish objective measures of concussion. Conventional neuroimaging is unable to detect structural changes to the brain associated with concussion. There is some evidence of micro-lesions and slight alterations to axonal tracks following concussion but for the most part the effects of concussion can be observed through functional changes in neural networks (Shaw, 2002; Hovda, 2014; Choe, 2016). These neurophysiological alterations are even felt at the cellular level with neurotransmitter release occurring at abnormal levels due to changes in neural ion channel activity from mechanoporation, as a result of injury (Choe, 2016). Small structural changes and alterations and the cellular level both provide evidence of neurophysiological

changes following concussion but larger scale changes to the functional connectivity of entire neural networks could be examined as a larger result of these neuropathological changes.

One such possibility that has been identified is through the examination of functional changes to some of the primary networks in the brain. There is evidence that functional connectivity in neural networks may be affected by concussion (Giza & Hovda, 2001; Hovda, 2014). One explanation for why networks may be disrupted following a concussion is due to dysfunctional neurovascular coupling.

Neurovascular Coupling and Neuro-Metabolism

One of the proposed mechanisms of dysfunction following concussion is reduced blood flow. Oxygen-rich blood is recruited to brain regions through a process called neurovascular coupling. In this process, neural activity is linked to increases in the metabolic rate of cerebral oxygen levels and ultimately cerebral blood flow (Ellis et al., 2016). Neurovascular coupling is carried out by activity in the neurons and glial cells, particularly astrocytes which have been shown to be instrumental in this process (Haydon & Carmignoto, 2006). Typically, more blood flow is recruited than necessary which supplies excess oxygen to the active brain regions (Haydon & Carmignoto, 2006). The excess oxygen is used to transport glucose or to remove metabolic waste products from the brain (Haydon & Carmignoto, 2006). In concussed individuals, there is evidence that there is less excess oxygen-rich blood recruited during neural activation caused by a disruption to neurovascular coupling (Haydon & Carmignoto, 2006; Jang et al., 2017). Without proper blood flow to necessary regions, brain activity can be affected, and functioning can be impaired.

Following a concussion, neurometabolic rates are altered. Disruptions occur at the molecular level leading to irregular ion channel activity and damage to the cell membrane

(Barkhoudarian, Hovda, & Giza, 2011). This process of disrupted ionic activity in the brain

following concussion is referred to as the neurometabolic cascade (Barkhoudarian et al., 2011;

Giza & Hovda, 2001). Without proper regulation, this flux of ions creates an increase of

excitatory neurotransmitters released, which places high demands on the Na^+/K^+ pump to re-

establish the electrochemical gradient required for proper cellular function (Barkhoudarian et al.,

2011). Additional energy is spent trying to re-establish the electrochemical gradient following

concussion leading to an increased need for glucose and metabolites in the brain to complete

cellular respiration (Giza & Hovda, 2001).

Due to interruptions in neurovascular coupling following concussion, there is difficulty

transporting additional glucose to the brain required to re-establish healthy metabolic processes

(Giza & Hovda, 2001). This results in what is deemed a neural energy crisis, because the brain

requires additional energy through glucose but cannot be supplied that energy due to limitations

in blood and oxygen flow to neural tissue (Giza & Hovda, 2011). Even though this energy crisis

is not permanent, it can lead to disruptions in neural functioning and cognitive processes

(Barkhoudarian et al., 2011).

The Default Mode Network

Our daily cognitive processes are reliant on healthy and proper functioning of closely

associated brain regions working together through electrical signals to form efficient neural

networks (Leech, Kamourieh, Beckmann, & Sharp, 2011). The default mode network is one of

many neural networks in the brain and in recent years has become an area of great interest in

current cognitive and affective neuroscience research.

The default mode network was originally also referred to as the task negative network as

it was activated during a resting state when a person is not actively concentrating or completing a

task (Leech et al., 2011). As research into the default mode network increased, it became clear that the default mode network was involved in more processes than just rest and not completing a task. This led researchers away from referring to the default mode network as the task negative network due to findings that suggest that the default mode network is influential in self-reflection, remembering past events, and planning for the future (Greicius, Krasnow, Reiss, & Menon, 2003; Greicius, Srivastava, Reiss, & Menon, 2004).

This default mode network is made up coordinated electrical neural signals between the ventromedial prefrontal cortex, the posterior cingulate cortex, and the ventral anterior cingulate cortex (Greicius et al., 2003; Greicius et al., 2004; Uddin, Kelly, Biswal, Castellanos, & Milham, 2009). Even though the default mode network is made up of many different complex brain regions the simplest task such as finger tapping is enough to deactivate it (Zhang et al., 2010).

Sex/Gender Differences in Default Mode Network Activity

Similar to concussion research, limited research into the differences between male and female default mode network activity has been completed. Slight sex/gender differences in the functional connectivity in the default mode networks have been observed. Due to the limited research in this field, there is not a consensus on whether there are differences in functional connectivity and default mode network activity between males and females.

In one study, females were found to have a stronger functional connectivity within the default mode network compared to males (Mak et al., 2017). Other studies suggest that there are possible differences in the rates of activation of the default mode network following the completion of specific task types between males and females but no noticeable differences in the functional connectivity of the default mode network between males and females (Weissman-Fogel et al., 2010; Dumais et al., 2018).

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The differences in the findings between studies could be related to the ages of the participants involved in the study. Functional connectivity in the default mode network has been found to be associated with age, and as an individual grows older, the functional connectivity of this neural network decreases (Scheinost et al., 2015). The decrease in functional connectivity is faster in males compared to females which could result in differences occurring in some studies and not others (Scheinost et al., 2015)

The Dorsal Attention Network

The dorsal attention network (DAN) is associated with goal oriented behaviour and sustained attention and focus on a task and is negatively correlated with default mode network activity. The dorsal attention network includes regions of the brain such as the inferior parietal sulcus, superior parietal lobule, and the dorsolateral prefrontal cortex (Spreng et al., 2016). This neural network is active when a person is actively engaged in a task and deactivates when a person is at rest or is not involved in goal directed behaviour (Dixon et al., 2017).

Since the dorsal attention network is anti-correlated to the default mode network, it shows low levels of activation during resting tasks and relaxation (Dixon et al., 2017; Spreng et al., 2016). Typically, as a person switches from completing a task to letting their mind wander, the dorsal attention network declines in activation and the default mode network increases its activity (Dixon et al., 2017; Spreng et al., 2016). Through functional neuroimaging of these networks, the levels of activation in these specific brain regions during active and resting tasks can be observed. Functional neuroimaging could be an important tool in better understanding the effects of neurological conditions, including traumatic brain injury that have been shown to negatively affect the default mode network and the dorsal attention network (Sours et al., 2013).

Functional Neuroimaging and Default Mode Network Research

Functional neuroimaging is the most common technique used to observe activity of neural networks such as the default mode network. Functional magnetic resonance imaging (fMRI) is the most common type of neuroimaging method used to conduct default mode network research (Zhang et al., 2010). Functional magnetic resonance imaging measures brain activity by detecting changes in blood flow throughout different brain regions (Zhang et al., 2010; Abbas et al., 2015). This technique uses a measure called the blood oxygen level dependent (BOLD) to measure the changes in oxygen levels in the blood in areas that are being scanned (Heeger & Ress, 2002).

Areas with higher levels of activation will show higher levels of oxygen, while areas of lower activation will have lower levels of oxygen present. The brain requires glucose and oxygen to complete its metabolic processes and function (Zhang et al., 2010). These metabolic processes allow functional neuroimaging techniques such as fMRI to utilize this fact and determine which regions of the brain are most active during specific cognitive processes (Heeger & Ress, 2002; Zhang et al., 2010).

Since the default mode network is activated when a person is at rest and not actively completing a task, studies observing the activity of this neural network often involve an active and a rest task. Including an active and rest task in default mode network studies allows researchers to observe the activation of this neural network when the person is at rest and then the inhibition of this network and the activation of attention networks such as the dorsal attention network that are engaged during goal directed behaviour (Bonnelle et al., 2012).

There are many different tasks that are used to inhibit the default mode network that can be utilized in functional neuroimaging studies that allow for activation of attention networks.

Tasks such as the n-back or 2-back task which are often used as a measure of working memory can easily inhibit the default mode network and are commonly used in functional neuroimaging studies (Esposito et al., 2006). These tasks present participants with a sequence of stimuli and require the participant to determine if the stimulus that is presented to them matches that of the one presented in the sequence a specific number of items ago (Kane et al., 2007).

Another commonly used testing method is the stop-signal task. This test requires participants to stop pressing a button when a sound stimulus changes and acts as the active state task for fMRI scans. The simplicity of this task makes it a very helpful task for conducting default mode network research on individuals with varying forms of traumatic brain injury as it places little cognitive strain on the individual but is still enough to deactivate the default mode network (Bonnelle et al., 2012)

Effects of Mild Traumatic Brain Injury on Default Mode Network Activity

Even though there is a limited but steadily growing body of research assessing the default mode network using functional neuroimaging, there is a very limited yet still important subset of this research assessing the effects of mild traumatic brain injury on the activity of this neural network. In an fMRI study, Bonnelle et al. (2012) effectively used a stop-signal task to inhibit the default mode network when assessing participants from both a healthy control population as well as a population that had sustained traumatic brain injuries ranging from mild to severe. Healthy participants in this study were able to quickly inhibit the default mode network and complete the task while those with traumatic brain injury took longer to engage the attention network and switch out of the resting state to perform the task.

Another study assessing individuals across various levels of traumatic brain injury found that individuals that had sustained a traumatic brain injury showed abnormal functional

connectivity in the default mode network as well as slower processing speeds and more difficulty completing the active tasks assigned in the study (Sharp et al., 2011). This study suggests that conditions such as traumatic brain injury that impact the functional connectivity and activation patterns of the default mode network can have effects that are directly observed through behaviour and performance as well as neuroimaging (Sharp et al., 2011).

Studies exclusively looking at mild traumatic brain have also found alterations in the functional connectivity of the default mode network and possible disruptions in memory functioning that is associated with this neural network shortly after concussion (Sours et al., 2013). Even though alterations in functional connectivity associated with default mode regions following some form of traumatic brain injury are a common result in neuroimaging studies, the consensus on if the functional connectivity increases or decreases following these injuries is not as clear (Zhou et al., 2012; Sours et al., 2013).

While oftentimes there is an observed decrease in functional activity in these regions following a concussion, there are also some studies that find the opposite. A study conducted by Sours et al. (2013) on 23 individuals with a mild traumatic brain injury found an increase in functional connectivity compared to the healthy controls. Similarly, Zhou et al. (2012) found that different regions of the default mode network exhibited different alterations in functional connectivity following a concussion. Regions of the posterior cingulate cortex and parietal regions of the default mode network were found to have decreased functional connectivity following a mild traumatic brain injury while default mode network regions near the medial prefrontal cortex showed increased functional connectivity (Zhou et al., 2012).

Even though there are some differing findings regarding functional connectivity of default mode network regions following a mild traumatic brain injury, alterations in the activity

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of this neural network that could lead to negative cognitive performance and functioning in individuals are consistent across the literature following concussion.

Effects of Sport-Related Concussion on Default Mode Network Activity

As the research into the effects of mild traumatic brain injury on default mode network activity grows, the need for more research understanding the particular but important type of mild traumatic brain injury, sport-related concussion, becomes even more crucial. Similar to the research findings across the different levels of traumatic brain injury, there are also differing findings regarding the effects of sport-related concussion on the default mode network.

Alterations in functional connectivity during the acute stage of sports-concussion have also been observed. In a 2016 fMRI study of concussed athletes, Militana et al. (2016) found increased functional connectivity in the default mode network within one week of concussion as well as no significant differences in cerebrovascular blood flow in the concussed athletes compared to healthy controls.

Conversely, Zhu et al. (2015) found that the alterations in functional connectivity following concussion could be related to the time since injury. An increase in functional connectivity one day after concussion was observed but then after that initial day, athletes showed a significant decrease in functional connectivity compared to healthy controls (Zhu et al., 2015). A possible explanation for this sudden increase in functional connectivity following a concussion followed by a decrease in functional connectivity could be associated with the neurometabolic cascade of concussion and the sudden increased demand and metabolic activity to specific brain regions following a brain injury (Giza & Hovda, 2001). However, this increased demand cannot be met following injury leading to the sharp decline in functional connectivity observed following the short initial increase.

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Mayer et al. (2011) and Johnson et al. (2012) found similar decreases in functional connectivity in the acute stage following sport-related concussion in athletes. These studies also found that athletes without a previous history of concussion returned to baseline functional connectivity within 30 days of concussion. Mayer et al. (2011) observed these decreases in functional connectivity across the posterior cingulate cortex and the anterior cingulate cortex and Johnson et al. (2012) observed these decreases in the posterior cingulate cortex and the dorsal lateral prefrontal cortex. The posterior cingulate cortex is involved in processes such as episodic memory and self-reflection and the disruptions to its functional connectivity following might be associated with some of the common symptoms observed in athletes following injury including trouble with memory and concentration (Johnson et al., 2012)

Research on male American high school football players found that repetitive concussions throughout a player's career produced long term changes to default mode network functional connectivity in the brain (Abbas et al., 2015). The functional connectivity of the default mode network was assessed using fMRI at 1 month, 2 months, 3 months, and 4 months post-concussion (Abbas et al., 2015). They found that the athletes that had sustained multiple concussions exhibited greater functional connectivity in default mode network regions such as the right anterior cingulate gyrus and the right middle frontal gyrus. The long lasting increased functional connectivity changes to the default mode network regions in these athletes with repetitive concussions was hypothesized to be a result of the metabolic cascade of concussion limiting the blood flow to the default mode network regions affected. As a result of a combination this metabolic slow down and multiple concussions which could possibly lead to alterations in some axonal tracts, the brain could use less common pathways and neural connections in the default mode network to carry out neural functioning in this region during

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recovery. With increased usage of these less common neural pathways, they will eventually strengthen over time leading to the observed increase in functional connectivity in these athletes that have sustained multiple concussions (Abbas et al., 2015).

Another study examining default mode network functional connectivity between one month and 48 months following concussion in rugby players found alterations in the default mode network (Johnson, Neuberger, Gay, Hallett, & Slobounov, 2014). In this study the differences in functional connectivity following a sport-related concussion were associated with the individual's past history of concussion. Those athletes with a greater number of past concussions showed a greater decrease in functional connectivity in default mode network regions (Johnson et al., 2014). Both studies found long-term alterations in the default mode network in repetitively concussed athletes beyond the acute phase of concussion typically lasting 2-3 weeks where people typically report symptoms.

These studies suggest that sport-related concussion could lead to alterations in default mode network functional connectivity and activation through changes in the BOLD response. The literature also demonstrates the importance of increased research into the area of default mode network research following sport-related concussion to better understand the effect of these injuries on the functional connectivity and activation of the neural network.

Future of Functional Neuroimaging Default Mode Network Research

Even though the default mode network can be deactivated by simple activities like pressing a button or tapping a finger, it is an important neural network involved in processes such as attention and episodic memory (Greicius et al., 2003). Limited research has been conducted looking at the effects of mild traumatic brain injury on default mode network activity,

and even less research has specifically examined sport-related concussion in regard to this neural network.

Although studies of the default mode network are traditionally conducted using fMRI, there are other viable alternatives for this type of research. Functional near infrared spectroscopy (fNIRS) is another less common but still effective form of functional imaging used in cognitive and affective neuroscience.

Functional Near Infrared Spectroscopy

Functional near infrared spectroscopy is a brain imaging technique that passes near-infrared light through the brain, utilizing the unique absorption properties of oxygenated and deoxygenated hemoglobin to detect brain activity (Irani, Platek, Bunce, Ruocco, & Chute, 2007; Ferrari & Quaresima, 2012). The wavelengths that fNIRS uses are between 700-900 nm because this is the optimal range of wavelengths for hemoglobin absorption and detection by the sensors (Ferrari & Quaresima, 2012). Areas of the brain with high levels of activity will require and recruit more oxygen than areas with low levels of activity in a process known as the hemodynamic response (Irani et al., 2007; Ferrari & Quaresima, 2012). This allows for the fNIRS sensors to create an image of oxygenated and deoxygenated hemoglobin perfusion based on the absorption of specific wavelengths associated with those molecules (Irani et al., 2007; Ferrari & Quaresima, 2012).

Advantages of fNIRS

There are some key advantages to fNIRS when compared to other more widely used functional neuroimaging techniques such as fMRI. The cost of an fMRI machine greatly out numbers that of fNIRS making the research much more expensive to conduct and therefore less accessible for smaller institutes or researchers without a large budget and access to an fMRI

machine of the concerns with fMRI is the cost of the machine (Logothetis, 2008). Another advantage of fNIRS over a technique such as fMRI is that fNIRS does not use magnetic resonance to record the BOLD response in the brain. Since fMRI uses magnetic resonance, all metal must be removed from the person being scanned. This makes it difficult for people with piercings, fillings, and even pacemakers, and cochlear implants to participate in fMRI research because if they cannot remove the metal from their body, they cannot undergo an fMRI scan (Logothetis, 2008). The loud sound produced by fMRI can cause possible hearing damage for people who require multiple scans whereas fNIRS is silent during scanning allowing for people to undergo multiple rounds of fNIRS scans without the risk of damage to their hearing (Logothetis, 2008).

Functional magnetic resonance imaging has poor temporal resolution compared to other imaging techniques such as EEG or fNIRS (Racine, Bar-Ilan, & Illes, 2005). Temporal resolution refers to the smallest amount of time required by a device to separate neural activity (Racine et al., 2005). Since neural activity is so quick, techniques with lower temporal resolution may miss some neural events that are occurring due to the sampling rate of the device. Functional near infrared spectroscopy also offers a greater range of mobility and allows for a wider range of tasks to be completed during the scan because the participant is not required to lay still in a machine for the duration of the scan (Racine et al., 2005).

Disadvantages of fNIRS

Even though there are some clear advantages to fNIRS as a functional neuroimaging technique compared to more common methods such as fMRI. There are some limitations to the capabilities of fNIRS. Functional near infrared spectroscopy has poor spatial resolution compared to its functional neuroimaging counterparts such as fMRI. (Pinti et al., 2018). Spatial

resolution is the clarity at which a neuroimaging can detect differences in locations of the brain. Similar to the poorer spatial resolution is the depth that the infrared light from the optodes can effectively reach in the brain. Only cortical brain regions are able to be observed using fNIRS as the techniques can reach brain regions with a depth of 1-2cm (Pinti et al., 2018).

A disadvantage observed across all types of neuroimaging is susceptibility to physiological noise such as heart rate and breathing and motion artifacts from the participant moving during the scan. While fNIRS has specific filters and processing techniques in place to control for this it is still an important to note this as a possible shortcoming to fNIRS as well as the other functional neuroimaging techniques (Logothetis, 2008; Pinti et al., 2018). Due to the relatively new nature of fNIRS, a set guideline for processing and analyzing the data has not been created, which leads to possible issues when comparing fNIRS studies due to the many different methods used to determine and interpret the results (Pinti et al., 2018).

Current Research

This research project was designed to further examine the effect of sport-related concussion on default mode network activity. Default mode network activity was assessed using fNIRS to measure BOLD response. There is a limited body of research into default mode network activity following mild traumatic brain injury or sport-related concussion. Within this research there have been many different findings regarding functional connectivity in default mode network associated regions following concussion. Some studies have found a decrease in functional connectivity following a concussion in default mode network regions (Mayer et al., 2011; Johnson et al., 2012; Zhou et al., 2012; Sours et al., 2013; Zhu et al., 2015), whereas other studies have found an *increase* in functional connectivity in default mode network regions following a concussion (Abbas et al., 2015; Zhu et al., 2015; Militana et al., 2016). Due to the

conflicting findings regarding the changes in functional connectivity in default mode network associated regions, there is currently not a consensus on exactly how this connectivity changes following a mild traumatic brain injury or sport-related concussion.

It is common for sport-related concussion research to focus on high contact sports such as American football, rugby, or ice hockey (Johnson et al., 2014; Nordström et al., 2014; Abbas et al., 2015). However, athletes across all sports were included in the current study to allow for greater generalizability and to allow for the study of gender effects (Abbas et al., 2015; Johnson et al., 2014; Nordström et al., 2014; Abbas et al., 2015). This study included both male and female participants in the control and concussed athlete groups as the growing body of literature has demonstrated differences in symptoms and recovery in males and females following concussion (Covassin et al., 2003, 2006, 2007, 2012; Broshek et al., 2005). The current research project aimed to take into consideration these differences as they could also translate to possible differences in default mode network activity following concussion.

Based on the previous research, it was hypothesized that individuals with mild traumatic brain injury would show increased activity of the default mode network when completing an active task. The second hypothesis was that athletes with sport-related concussion would have a longer latency switching between the activated and deactivated states of the default mode network during active and resting tasks, compared to the control group. Based on previous literature suggesting that female athletes tend to report more symptoms and a higher level of symptom intensity compared to male athletes and often require a longer recovery period (Covassin et al., 2003, 2006, 2007, 2012; Broshek et al., 2005) differences in default mode network activity in male and female athletes following a sport-related concussion were expected. Female athletes were expected to show greater differences in default mode network activity

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compared to male athletes Research into concussion suggests that these differences may be exacerbated due to differing trajectories of recovery often observed between male and female athletes following a sport-related concussion.

The third research question was does sex/gender have an effect on default mode network activity in healthy control individuals. Limited research in the past suggests that there may be slight differences in default mode network activity between healthy male and female controls.

CHAPTER 2

Methods

Participants

A total of 20 participants were recruited for this study. Participants in this study consisted of 3 athletes (Mean age = 21.33, SD = 0.577; 2/3 female) with a sport-related concussion and 15 individuals without a sport-related concussion (Mean age = 21, SD = 2.64; 9/15 female) acting as a control group as well as a group of 2 athletes without a sport-related concussion (Mean age = 22, SD = 0; 2/2 female). Data collection for the athletes ended prematurely due to COVID-19 restrictions on sports and in-person research. The athletes participating in this study were all recruited from sports teams at the University of Windsor. Athletes involved in this research completed a clinical evaluation administered by the University of Windsor's Sports Related Concussion Centre and completed the study within three weeks of injury during the acute stage of concussion. The control groups were recruited from the University of Windsor's Undergraduate Participant Pool.

Materials

fNIRS System

The fNIRS device used for data acquisition in this study was a frequency domain system (Imagent, ISS Inc., Champaign, IL). This system consisted of 8-fibre optic cables (light sources) and 2 detectors, forming a total of 8 optodes (source-detector pairs) and 16 channels. The light emitted from the fibre optic cables was intensity modulated at a frequency of 110 MHz. Two wavelengths (830nm and 690nm) were used to measure the concentration of oxygenated and deoxygenated hemoglobin. The distance between each source and detector pair was 3cm and two short distance sources was placed 1 cm away from each detector to control for physiological noise.

The fNIRS headband was custom made using neoprene and plastic (see Figure 1). The fNIRS' probes were secured to the head using 3D printed components and Velcro straps and buckles. The headband was positioned on the forehead and probes were aligned using 10-20 coordinates (see Figure 2). Temporary markings using chalk/charcoal were made to ensure optimal positioning for the fNIRS cap on the participant. Once the cap was secured, the participants hair was parted using a soft plastic rod to allow for a clear view of the scalp. After the hair was parted the optodes were lowered into the slots on the cap and secured down to the scalp. Only after all of the optodes were properly secured the fNIRS system will be powered on to prevent any accidental exposure to the laser light.

Once the lasers were activated, the data collection software began recording and a check for signal optimization was performed. If the signal strength was suboptimal due to an obstructed view of the scalp from hair or the optodes not being secured tightly enough, the

apparatus was powered down and the optodes were removed and reseated. This process continued until an optimal signal was observed.

The brain regions observed in this study consisted of cortical areas because fNIRS is not capable of recording activation of deep brain structure. The brain regions of interest for the default mode network and attention network consist of the medial prefrontal cortex and dorsal later prefrontal cortex, respectively (See Table 1).

Procedure

Stop-Signal and Rest Task

After consenting to participate, participants were seated in front of a computer and the fNIRS apparatus was setup. Two researchers were present for the entirety of the study to assist with the fNIRS apparatus. Once the fNIRS apparatus was secured, the lights in the room were lowered and the participants were seated in front of a computer screen with a filter and backlight to reduce the visual strain on the concussed individuals.

Participants in this study underwent an fNIRS scan to assess the activity of the default mode network. To measure the oxygenated and deoxygenated hemoglobin in the brain, 830 nm and 690 nm wavelengths were used. The fNIRS scan lasted for a total of thirty minutes.

Each participant completed a three-minute stop-signal task (see Figure 3). During this task, the participant was instructed to press left and right arrow keys on a keyboard as arrows pointing either left or right appear on a computer screen. These arrows appeared every second in a randomized order. A one second audio signal was played randomly and occurred once during every five second interval. The participants were instructed to not click any key for the arrows that occurred with the audio signal. Following the completion of the audio signal, the participant resumed pressing the button. Following the completion of the active task, a three-minute resting

task began. Participants were instructed to close their eyes and let their mind wander. The stop-signal task and resting alternated order and repeated for a total of five trials each.

Data Analysis and Statistics

Pre-processing fNIRS Data

Changes in the concentration of oxygenated and deoxygenated hemoglobin were be derived from raw fNIRS data over sixteen channels that consisted of eight source detector pairs over two wavelengths (690nm and 830nm). Raw data were collected using Boxy software from ISS Inc. and preprocessed using the Homer2.0 (Huppert, Diamond, Franceschini, & Boas, 2009) software package. This preprocessing of data was completed to improve signal to noise ratio through normalization, correcting for signal drifts and motion artifacts. A low pass filter (0.5Hz) and a high pass filter (0.01Hz) were applied to remove the effects of cardiac and respiratory cycles.

Pre-processing of fNIRS data also included a visual inspection of the data during the data collection and following the completion of the experiment for each of the 20 participants. This visual inspection was completed using the BOXY software provided by ISS Imagent (ISS Medical, 2016) and was done to determine if an adequate signal strength was recorded during the experiment. All 20 participants were deemed to have had an adequate signal strength during experimentation and all of the participants were included in the analysis. The criteria used for determining adequate signal strength followed the guidelines stated by Orihuela-Espina et al. (2010). Orihuela-Espina et al. (2010) required an average amplitude (AC signal) of greater than 100, magnitude (DC signal) of 2000, and a signal variance (phase) of less than 10 for the overall signal quality to be determined adequate for inclusion in analysis.

Additionally, short signal optodes which capture surface and skin vascular change were used allowing for removal of non-cortical vascular changes. This short signal processing followed the algorithm derived by the hmrDeconvHRF_DriftSS function in the Homer2.0 package (Hupert et al., 2009). This produced a clean function of concentration for each optode throughout the course of the experiment for oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin (HbT).

Once the file was converted the data was quantitatively analyzed. The data recorded from the concussed and control groups was appropriately labelled and analyzed separately. Default mode network activity during all of the active and resting tasks was analyzed for each participant across the different groups.

The data was separated into epochs based on task conditions. The epochs were divided into a three-minute active trial followed by a three-minute rest trial. These trials alternated order and repeat for a total of five trials each. Signal separation was optimized using a short-signal general linear model (GLM) algorithm which allows for the separation of the hemodynamic response for each epoch (Gagnon et al., 2014). Through this GLM algorithm, a graph of the hemodynamic response is created and from that graph the hemodynamic response function (HRF) can be estimated using a GLM. This GLM uses the least squares method to create beta coefficients which are the values used for analysis in the fNIRS study. These beta coefficients are the product of a linear regression analysis over the whole hemodynamic response function for each participant.

Each participant's signal was averaged across trials, producing mean concentration patterns for each epoch. Analyses were conducted across groups (concussed and control) averaging these epochs across participants. This groups were run through the algorithm to

separate the BOLD signals across their epochs. After this process the data can be run across the groups and separated into male and female for each group to run analysis on gender/sex differences. These patterns were then applied to a brain atlas to demonstrate activity patterns to show a visual demonstration between conditions and groups.

Statistical Analysis of fNIRS Data

The statistical analysis of the fNIRS data involved completing independent samples t-test on the pre-processed data that was in the form of GLM-generated beta coefficients to evaluate possible differences in the hemodynamic responses in default mode network activity among the different groups during the active and rest tasks. The hemodynamic response evaluated was during the first 15-20 seconds of each of the tasks as this is the earliest point that changes in these signals will be observed. The Benjamini-Hochberg False Discovery Rate (FDR) method with a false discovery rate of 0.05 was used in this analysis to control for possible type 1 error due to the number of comparisons made.

Analysis of the possible effect of sex/gender on default mode network activity in healthy controls as well as concussed participants was also included in the in planned statistical analysis. The statistical analysis completed for this study involved comparisons between each of the fNIRS optodes, the type of hemoglobin (HbO, HbR, HbT, and group (concussed, control, control athlete). This was done for the rest period (see Tables 2 and 4) and active task period (see Tables 3 and 5).

Qualitative analysis was done using the models created through the visual brain atlas diagrams that were created as a representation of the processed data.

Results

Independent samples t-tests were conducted on the average beta coefficients derived from the hemodynamic response function during the 15-20 second period following the rest of active task period. A Benjamini-Hochberg False Discovery Rate (FDR) correction was applied to account for multiple comparisons. The p-values from the independent samples t-tests are represented in Tables 2-5. Visual representation of the different default mode network regions analyzed were created through 3D brain maps that overlayed the group mean results of the beta coefficients onto a diagram (see Figures 4-13). Channel 4.2 was removed from analysis due to poor quality signal across multiple groups.

Effect of Concussion on Default Mode Network during Rest Task

Significant differences were found between concussed female athletes (M = 3.86×10^{-7}, SD = 2.76×10^{-8}) and control females (M = -1.13×10^{-7}, SD = 2.54×10^{-7}) in HbT in optode 2.1; t(8.64) = -5.75, p = 0.002; (r^2 = 0.308) and concussed female athletes (M = 2.76×10^{-7}, SD = 1.06×10^{-7}) and control females (M = -1.27×10^{-7}, SD = 2.41×10^{-7}) in HbT in optode 3.1; t(8.13) = -4.98, p = 0.007; (r^2 = 0.243) during the rest task (See table 2). No significant differences were found in the comparisons between the overall concussed athlete group and the control group across any of the optodes for any of the types of hemoglobin during the rest task. No significant differences were found in the comparisons between the concussed athlete group and the control athlete group across any of the optodes for any of the types of hemoglobin during the rest task. No significant differences were found in the comparisons between the female concussed athlete group and the control female athlete group across any of the optodes for any of the types of hemoglobin during the rest task.

Effect of Concussion on Default Mode Network during Active Task

Significant differences were found between concussed female athletes (M = 3.00 x 10^{-7}, SD = 1.39 x 10^{-8}) and control females (M = -5.37 x 10^{-7}, SD = 1.47 x 10^{-7}) in HbT in optode 1.1; t(8.55) = -7.085, p = 0.001; (r^2 = 0.400) and between concussed female athletes (M = 3.00 x 10^{-7}, SD = 1.39 x 10^{-8}) and control female athletes (M = -1.39 x 10^{-7}, SD = 2.77 x 10^{-8}) in HbT optode 1.1; t(1.47) = 20.01, p = 0.031; (r^2 = 0.995) during the active task (See table 3). No significant differences were found in the comparisons between the overall concussed athlete group and the control group across any of the optodes for any of the types of hemoglobin during the active task. No significant differences were found in the comparisons between the concussed athlete group and the control athlete group across any of the optodes for any of the types of hemoglobin during the active task.

Default Mode Network Differences in Healthy Individuals during Rest Task

Significant differences were found between control participants (M = -1.57 x 10^{-7}, SD = 2.77 x 10^{-7}) and control athletes (M = 2.60 x 10^{-7}, SD = 6.81 x 10^{-8}) in HbT in optode 1.1; t(7.59) = 4.84, p = 0.01; (r^2 = 0.133) and control participants (M = -1.87 x 10^{-7}, SD = 2.33 x 10^{-7}) and control athletes (M = 1.71 x 10^{-7}, SD = 7.55 x 10^{-8}) in HbT in optode 2.1; t(4.61) = 4.46, p = 0.028; (r^2 = 0.137) and control participants (M = -1.82 x 10^{-7}, SD = 3.25 x 10^{-7}) and control athletes (M = 1.20 x 10^{-7}, SD = 5.61 x 10^{-8}) in HbT in optode 5.2; t(12.317) = 3.26, p = 0.046; (r^2 = 0.055) during the rest task. Significant differences were found between control females (M = -1.43 x 10^{-7}, SD = 2.19 x 10^{-7}) and control female athletes (M = 2.60 x 10^{-8}, SD = 6.82 x 10^{-8}) in HbT in optode 1.1; t(6.534) = -4.612, p = 0.010; (r^2 = 0.279) (See table 4). Significant differences were not found in the comparisons between the overall control males and control females across any of the optodes for any of the types of hemoglobin during the rest task.

Default Mode Network Differences in Healthy Individuals during Active Task

No significant differences were found in the comparisons between control males and control females across any of the optodes for any of the types of hemoglobin during the active task (See table 5). No significant differences were found in the comparisons between the control group and the control athlete group across any of the optodes for any of the types of hemoglobin during the active task. No significant differences were found in the comparisons between the female control group and the control female athlete group across any of the optodes for any of the types of hemoglobin during the active task.

Discussion

Concussed female athletes showed lower concentrations of total hemoglobin compared to control females in optodes 2.1 (Brodmann Area 8; Middle Frontal Gyrus) and 3.1 (Brodmann Area 9; Dorsolateral Prefrontal Cortex) during the rest task. When cortical areas are active this is marked by an increase in oxygenated hemoglobin and total hemoglobin as well as a decrease in deoxygenated hemoglobin (Kamran, Mannan, & Jeong, 2016). This indicates less blood flow to these default mode network regions during the rest task in concussed female athletes compared to controls, suggesting a decrease in default mode network activity. Decreased default mode network activity during a rest tasks indicates concussed females had more difficulty engaging the default mode network, or disengaging from networks associated with the active task, which is expected to reach its peak levels of activity during the rest task.

This decreased default mode network activity and increased difficulty disengaging from networks associated with the active task is consistent with the idea that following concussion, there is a neurometabolic cascade causing increased demand for blood flow, combined with decreased neurovascular coupling, to the regions affected by the concussion resulting in

decreased functional connectivity and activity to those regions (Giza & Hovda, 2001). This decreased level of functioning in default mode network regions may be associated with some of the symptoms commonly reported following a concussion such as issues with episodic memory and difficulty focusing which are cognitive processes typically carried out in part by the default mode network (Prince & Bruhns, 2017; Scorza & Cole, 2019).

Zhou et al. (2012) and Zhu et al. (2015) found decreased functional connectivity in default mode network associated regions following concussion which could result in this abnormal pattern of default mode network activation and even be related to possible attentional deficits in the recovery period of concussion. The decreases in functional connectivity found by Zhou et al. (2012) examined a population of 23 (17 male) individuals with a mean age of 37 years for mild traumatic brain injury. These individuals were not athletes, and these were any form of mild traumatic brain injury not specifically refined to sport-related concussion.

Oftentimes research examining the effects of mild traumatic brain injury on default mode network activity involves adult and middle-aged participants it is difficult to directly compare those findings to those of the research being done looking specifically at sport related concussion which tends to involve participants at the high school and collegiate level. There is some literature that suggests as people age, possible functional connectivity differences in healthy individuals may start to arise. The varying age ranges recruited in different studies could be one of the reasons there are differences between studies regarding functional connectivity in the default mode network following concussion (Boraxbekk et al., 2016).

However, a decrease in functional connectivity was also found by Zhu et al. (2015) who looked specifically at sport-related concussion and found these differences seven days post injury during the acute stage of concussion. This study specifically examined eight concussed collegiate

male football players and 11 male control individuals both with a mean age of 20 years. Their findings provided evidence of decreased functional connectivity in default mode network regions such as the posterior cingulate cortex during the acute phase of concussion.

Significant differences were also found in total hemoglobin concentrations when comparing control participants and control athletes in optodes 1.1 (Brodmann Area 9; Dorsolateral Prefrontal Cortex), 2.1 (Brodmann Area 8; Middle Gyrus) and 5.2 (Brodmann Area 10; Anterior Prefrontal Cortex) as well as between control female participants and control female athletes in optode 1.1 (Brodmann Area 9; Dorsolateral Prefrontal Cortex) during the rest task. Control athletes showed greater total hemoglobin concentration compared to the non-athlete controls in these regions.

This concentration difference indicates that there was overall greater default mode network activation in these regions for control athletes, compared to the non-athlete controls at rest. Greater default mode network activation at rest is consistent with previous findings that those who live an active lifestyle may have greater functional connectivity in the default mode network (Boraxbekk et al., 2016).

No significant differences were found between male and female controls in either rest or active task across any of the optodes for any of the types of hemoglobin. This result is consistent with some past findings that suggest that healthy control males and females do not exhibit differences in default mode network activity (Dumais et al., 2018). In their study, Dumais et al. (2018) found that there were not significant differences between males and females in default mode network activity during the completion on tasks without an emotional valence. n-back working memory tasks used to deactivate the default mode network did not produce significant

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differences in default mode network between these groups similar to the results found in this study.

The sample size for the significant differences found in this study is small, limiting the ability to draw solid conclusions regarding the concentration differences found in default mode network regions between the groups measured.

Limitations

There were significant limitations on data collection for this study due to the COVID-19 pandemic. Data collection was halted a year prior to the intended date resulting in a smaller than anticipated sample size. Due to this, only a small number of concussed (n=3) and control athletes (n=2) were able to be recruited as the main sporting season was cancelled due to the pandemic. This limited the ability to carry out sex/gender-based analysis on concussed athletes as well as healthy control athletes on default mode network activity as only one concussed male athlete was able to be recruited and the control athletes were only female.

Another possible limitation of this study is controlling the amount of physical activity performed by the athlete group and the control group. A physical activity scale was originally intended to be used for this study but could not be implemented due to COVID-19 ending data collection for this study. Additionally, information regarding menstrual cycles in the female participants was intended to be recorded however this was also not able to be collected in the participants as data collection was cut before this measure was added to the study. Blood pressure was another measure intended to be measured in each participant that was not able to be added into the study due to data collection being cut short due to COVID-19. Controlling for these measures could help reduce the effects of extraneous variables on default mode network activity ensuring the signal observed is a result of the intended experimental measures.

Due to there not being a standardized method for pre-processing and analyzing fNRIS data, it is difficult to make comparisons to other fNIRS or even fMRI studies as they might be using techniques that are more liberal or conservative than the methods used in the current study. Due to this fact, data that is considered insignificant in this analysis might have been significant in a different fNIRS study as different processing and analysis methods were used.

After seating the optdoes on the participants they are instructed to avoid movement as much as possible in order to ensure that the optodes do not become displaced or unseated during the experiment. Even though limited movement was observed in the participants during the experimentation subtle movements may lead to shifting of the optodes on the participants. These slight shifts may alter the specific area of the brain that is being recorded.

Modifications could be made to the fNIRS testing apparatus to ensure effective signal collection across all participants. Channel 4.2 was excluded from the analysis due to a weak signal produced during the experimental procedure across all participants. A more precise mapping technique such as a computerized digitization process as opposed to the manually placed 10-20 system could help ensure exact location of the fNIRS optodes.

Future Research

Research involving individuals with a past history of concussion could be conducted in the future to better understand the effect of multiple concussions on default mode network activity. Studies in the past have found that athletes with repetitive concussions have significantly worse functional connectivity in default mode network regions (Abbas et al., 2015). These differences in functional connectivity can even be observed outside of the acute stage of concussion where symptoms are present (Johnson et al., 2014). Individuals with a single concussion are not likely to exhibit these changes in functional connectivity long term and

usually return to normal default mode network functioning after the acute stage of concussion (Zhu et al. (2015).

Recruiting athletes at the beginning of the season and performing a baseline fNIRS default mode network scan and then assessing the same athletes again if they are concussed during the season could provide possible strong insights into the effects of sport-related concussion on default mode network activity. Comparing an athlete's default mode network baseline to their concussed score could help in the development of a possible biomarker for concussion. This biomarker could then be used for baseline testing and avoid underreporting concussions through measures such as sandbagging because neuroimaging would capture the activity in these regions as opposed to a self-reported measure.

Performing multiple fNIRS scans on participants in a longitudinal study could also provide valuable information about the effect of concussion on default mode network activity during different periods following concussion. Some studies in the past have found that functional connectivity of the default mode network following concussion is associated with the time since injury (Zhu et al., 2015). Examining athletes at different times including immediately after concussion could help further examine these differences in default mode network activity at different time periods during injury.

Further examinations of sex/gender differences should be completed in future default mode network activity research. With the growing body of literature showing differences between males and females following concussion in both the severity of concussion symptoms as well as the recovery from concussion, it is vital that female athletes are recruited and analyzed distinctly in concussion research (Covassin et al., 2003, 2006, 2007, 2012; Broshek et al., 2005).

Finally, further examining the effects of physical activity on default mode network activity could help disentangle whether athletes naturally have different levels of default mode network activity compared to normal controls, or whether it is due to their more active lifestyles. Findings in the past suggest that those who live a healthy and active lifestyle over a long period of time show higher levels of functional connectivity in the default mode network compared to those that are not as active (Boraxbekk et al., 2016). These results suggest that competitive varsity athletes may have higher baseline functional connectivity in default mode network regions compared to controls due to their lifestyle.

Implications

This study helped better understand the effects of sport related concussion on default mode network activity. It also included three distinct groups control individuals, control athletes and concussed athletes which allowed for comparisons to see if an athlete's active lifestyle affected their default mode network activity compared to the traditional control group used in previous studies. This study also aimed to recruit male and female participants in all of its groups to ensure that sex/gender were being taken into consideration in analysis as opposed to many studies in the past that focused mainly on male athletes (Johnson et al., 2014; Abbas et al., 2015). This study utilized fNIRS as opposed to fMRI and provided more research into the fNIRS neuroimaging field to help increase its validity in a clinical setting.

Conclusion

Even though there were limitations to this study due to restricted data collection measures as a direct cause of the COVID-19 pandemic, it still demonstrates the importance of furthering research into sport-related concussion. Applying the previously mentioned modifications to this study and increasing the sample size to the intended number could help better elucidate the

effects of concussion as well as sex/gender on default mode network activity. This study also helped to increase the validity of fNIRS as a functional neuroimaging technique through its use to collect and analyze data as well as to help establish a set pre-processing and analysis technique for fNIRS data through thoroughly reporting all of the pre-processing and analysis techniques used.

The significant differences detected in this data indicate the importance of sex/gender based analysis in concussion research as well as default mode network research as a whole. This study also underscores the importance of better understanding the effects of sport-related concussion on the health of athletes due to its prevalence as health condition worldwide and the possible long-term effects that can be felt by athletes suffering repetitive concussions throughout their lifetime.

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Appendix A: Tables

Table 1.

fNIRS receptor locations and brain regions

Channels	MNI Coordinates			Brodmann Area	Region
	x	y	z		
1	34	25	31	9	Dorsolateral Prefrontal Cortex
2	26	31	32	8	Middle Frontal Gyrus
3	26	38	29	9	Dorsolateral Prefrontal Cortex
4	48	46	22	10	Anterior Prefrontal Cortex
5	22	70	2	10	Anterior Prefrontal Cortex
6	18	58	-1	10	Anterior Prefrontal Cortex
7	24	60	0	10	Anterior Prefrontal Cortex
8	34	28	25	9	Dorsolateral Prefrontal Cortex

Note. Channels represent the detectors used to gather the signal. Channels 7 and 8 were surface level detectors and were not used to measure the activity of the cortex they were placed at.

Table 2.

p-values for Oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total

hemoglobin (HbT) concentration changes for rest task compared to concussed athletes

Channel	Brodmann Area	Cortical Region	Conc vs Ctrl HbO HbR HbT	Conc vs Ctrl Ath HbO HbR HbT	Conc (F) vs Ctrl (F) HbO HbR HbT	Conc (F) vs Ctrl Ath (F) HbO HbR HbT
				# of Participants		
			Conc / Ctrl	Conc / Ctrl Ath	Conc (F) / Ctrl (F)	Conc (F) / Ctrl Ath (F)
			3 / 15	3 / 2	2 / 9	2 / 2
1.1	9	Dorsolateral Prefrontal Cortex	0.308 >0.99 0.386	0.277 >0.99 0.232	0.158 0.783 0.484	0.307 >0.99 0.512
2.1	8	Middle Frontal Gyrus	0.596 >0.99 0.161	0.986 0.770 0.725	0.290 0.865 **0.002**	0.504 0.744 0.143
3.1	9	Dorsolateral Prefrontal Cortex	0.681 0.249 0.068	0.810 0.878 0.707	0.548 0.697 **0.007**	0.755 0.983 0.964
4.1	10	Anterior Prefrontal Cortex	0.270 >0.99 0.408	0.926 >0.99 0.817	0.218 >0.99 0.274	0.658 0.912 0.747
5.2	10	Anterior Prefrontal Cortex	0.060 0.939 0.296	0.334 0.973 >0.99	0.087 >0.99 0.700	0.366 0.983 0.940
6.2	10	Anterior Prefrontal Cortex	0.893 >0.99 0.902	0.781 >0.99 >0.99	0.986 >0.99 >0.99	0.867 >0.99 0.924

Abbreviations. MNI = Montreal Neurological Institute and Hospital; Ctrl = Control; Conc = Concussed; Ath = Athlete; (F) = Female; HbO = Oxygenated Hemoglobin; HbR = Deoxygenated Hemoglobin; HbT = Total Hemoglobin. *Note.* Independent samples t-tests were conducted on beta coefficients that were a result of the linear regression of hemoglobin concentrations to the HRF. The p-values displayed were obtained from independent samples t-tests conducted on beta coefficients obtained from the 15-20 second range of the rest task.

Table 3.

p-values for Oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin (HbT) concentration changes for active task compared to concussed athletes

Channel	Brodmann Area	Cortical Region	Conc vs Ctrl HbO HbR HbT	Conc vs Ctrl Ath HbO HbR HbT	Conc (F) vs Ctrl (F) HbO HbR HbT	Conc (F) vs Ctrl Ath (F) HbO HbR HbT
			# of Participants			
			Conc / Ctrl	Conc / Ctrl Ath	Conc (F) / Ctrl (F)	Conc (F) / Ctrl Ath (F)
			3 / 15	3 / 2	2 / 9	2 / 2
1.1	9	Dorsolateral Prefrontal Cortex	0.423 >0.99 0.435	0.216 >0.99 0.467	0.201 >0.99 **0.001**	0.201 >0.99 **0.031**
2.1	8	Middle Frontal Gyrus	0.383 >0.99 0.279	0.490 0.917 0.494	0.863 >0.99 0.518	0.748 0.885 0.570
3.1	9	Dorsolateral Prefrontal Cortex	0.713 0.948 >0.99	0.895 >0.99 0.633	0.731 0.567 0.712	>0.99 0.665 0.696
4.1	10	Anterior Prefrontal Cortex	0.411 0.927 0.485	0.349 0.988 0.234	0.996 >0.99 0.715	0.282 0.988 0.375
5.2	10	Anterior Prefrontal Cortex	>0.99 0.799 >0.99	>0.99 >0.99 >0.99	0.928 0.756 >0.99	>0.99 0.945 0.968
6.2	10	Anterior Prefrontal Cortex	>0.99 0.393 0.560	>0.99 0.538 0.696	>0.99 0.425 0.586	>0.99 0.528 0.716

Abbreviations. MNI = Montreal Neurological Institute and Hospital; Ctrl = Control; Conc = Concussed; Ath = Athlete; (F) = Female; HbO = Oxygenated Hemoglobin; HbR = Deoxygenated Hemoglobin; HbT = Total Hemoglobin. *Note.* Independent samples t-tests were conducted on beta coefficients that were a result of the linear regression of hemoglobin concentrations to the HRF. The p-values displayed were obtained from independent samples t-tests conducted on beta coefficients obtained from the 15-20 second range of the active task.

Table 4.

p-values for Oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total

hemoglobin (HbT) concentration changes for rest task comparing the control groups

Channel	Brodmann Area	Cortical Region	Ctrl (F) vs Ctrl (M) HbO HbR HbT		Ctrl vs Ctrl Ath HbO HbR HbT		Ctrl (F) vs Ctrl Ath (F) HbO HbR HbT	
					Participants			
			Ctrl (F)	Ctrl (M)	Ctrl	Ctrl Ath	Ctrl (F)	Ctrl Ath (F)
			9	6	15	2	9	2
1.1	9	Dorsolateral Prefrontal Cortex	0.644 0.324 0.839		0.179 0.849 **0.010**		0.326 0.856 **0.010**	
2.1	8	Middle Frontal Gyrus	0.344 >0.99 0.142		0.419 >0.99 **0.028**		0.363 0.646 0.059	
3.1	9	Dorsolateral Prefrontal Cortex	0.741 0.373 0.734		0.961 0.053 0.668		0.970 0.222 0.672	
4.1	10	Anterior Prefrontal Cortex	0.686 >0.99 0.333		0.161 >0.99 0.349		0.284 0.983 0.356	
5.2	10	Anterior Prefrontal Cortex	0.560 >0.99 0.935		0.113 >0.99 **0.046**		0.118 >0.99 0.057	
6.2	10	Anterior Prefrontal Cortex	>0.99 0.958 0.864		0.923 >0.99 0.583		0.965 >0.99 >0.99	

Abbreviations. MNI = Montreal Neurological Institute and Hospital; Ctrl = Control; Conc = Concussed; Ath = Athlete; (F) = Female; (M) = Male; HbO = Oxygenated Hemoglobin; HbR = Deoxygenated Hemoglobin; HbT = Total Hemoglobin. *Note.* Independent samples t-tests were conducted on beta coefficients that were a result of the linear regression of hemoglobin concentrations to the HRF. The p-values displayed were obtained from independent samples t-tests conducted on beta coefficients obtained from the 15-20 second range of the rest task.

Table 5.

p-values for Oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total

hemoglobin (HbT) concentration changes for active task comparing the control groups

Channel	Brodmann Area	Cortical Region	Ctrl (F) vs Ctrl (M) HbO HbR HbT		Ctrl vs Ctrl Ath HbO HbR HbT		Ctrl (F) vs Ctrl Ath (F) HbO HbR HbT	
			Participants					
			Ctrl (F)	Ctrl (M)	Ctrl	Ctrl Ath	Ctrl (F)	Ctrl Ath (F)
			9	6	15	2	9	2
1.1	9	Dorsolateral Prefrontal Cortex	0.674 >0.99 0.564		0.700 >0.99 0.692		0.514 0.983 0.328	
2.1	8	Middle Frontal Gyrus	0.713 >0.99 0.829		0.959 >0.99 0.986		0.958 >0.99 0.999	
3.1	9	Dorsolateral Prefrontal Cortex	0.822 0.848 0.980		0.782 0.811 0.838		0.806 0.933 0.707	
4.1	10	Anterior Prefrontal Cortex	0.299 0.255 0.599		0.220 >0.99 0.126		0.212 0.758 0.086	
5.2	10	Anterior Prefrontal Cortex	>0.99 >0.99 >0.99		>0.99 >0.99 >0.99		>0.99 >0.99 >0.99	
6.2	10	Anterior Prefrontal Cortex	0.979 0.349 0.663		>0.99 0.387 0.660		>0.99 0.349 0.736	

Abbreviations. MNI = Montreal Neurological Institute and Hospital; Ctrl = Control; Conc = Concussed; Ath = Athlete; (F) = Female; (M) = Male; HbO = Oxygenated Hemoglobin; HbR = Deoxygenated Hemoglobin; HbT = Total Hemoglobin. *Note.* Independent samples t-tests were conducted on beta coefficients that were a result of the linear regression of hemoglobin concentrations to the HRF. The p-values displayed were obtained from independent samples t-tests conducted on beta coefficients obtained from the 15-20 second range of the active task.

Appendix B: Figures

Figure 1. fNIRS device and setup

The fNIRS cap is mounted on participants sitting in front of a computer screen where they will

complete the active and rest portion of the experiment. The cap is custom designed using

neoprene and plastic and utilizes Velcro and straps to tighten and remain in place during the
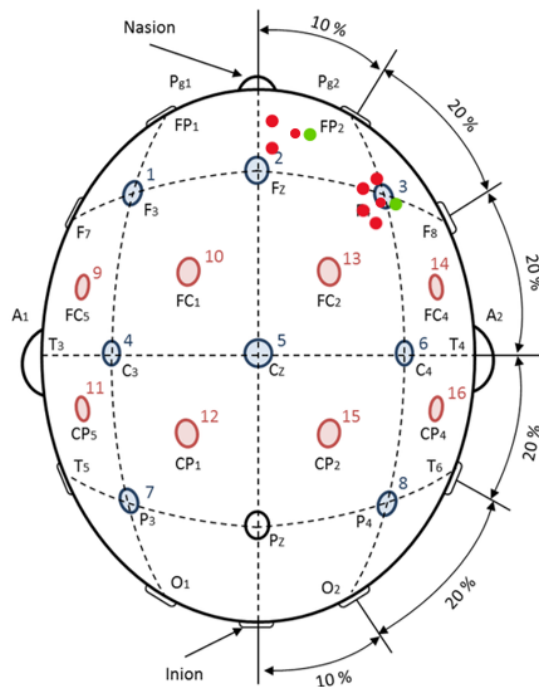
duration of the study.

Figure 2. 10-20 coordinate system for placement of fNIRS optodes.

Detectors are represented by green dots. Sources are represented by red dots. Sources are 3cm apart and short distance sources are 1cm away from their appropriate detectors. Retrieved from http://openbci.com/community/how-to-make-your-openbci-eeg-headset-comfortable-3/
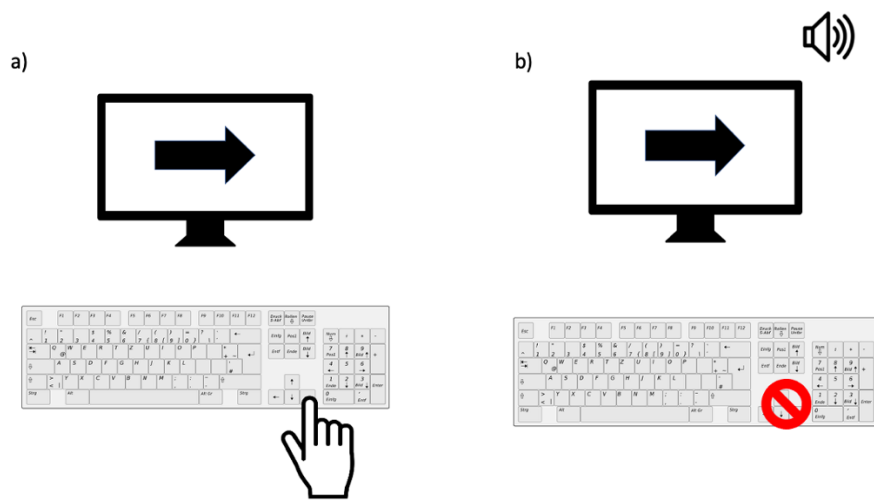
Figure 3.Stop Signal Task.

a) The participant clicks the right direction key on the keyboard as a right facing arrow appears

on the screen. b) A sound plays as the right facing arrow appears on the screen and the

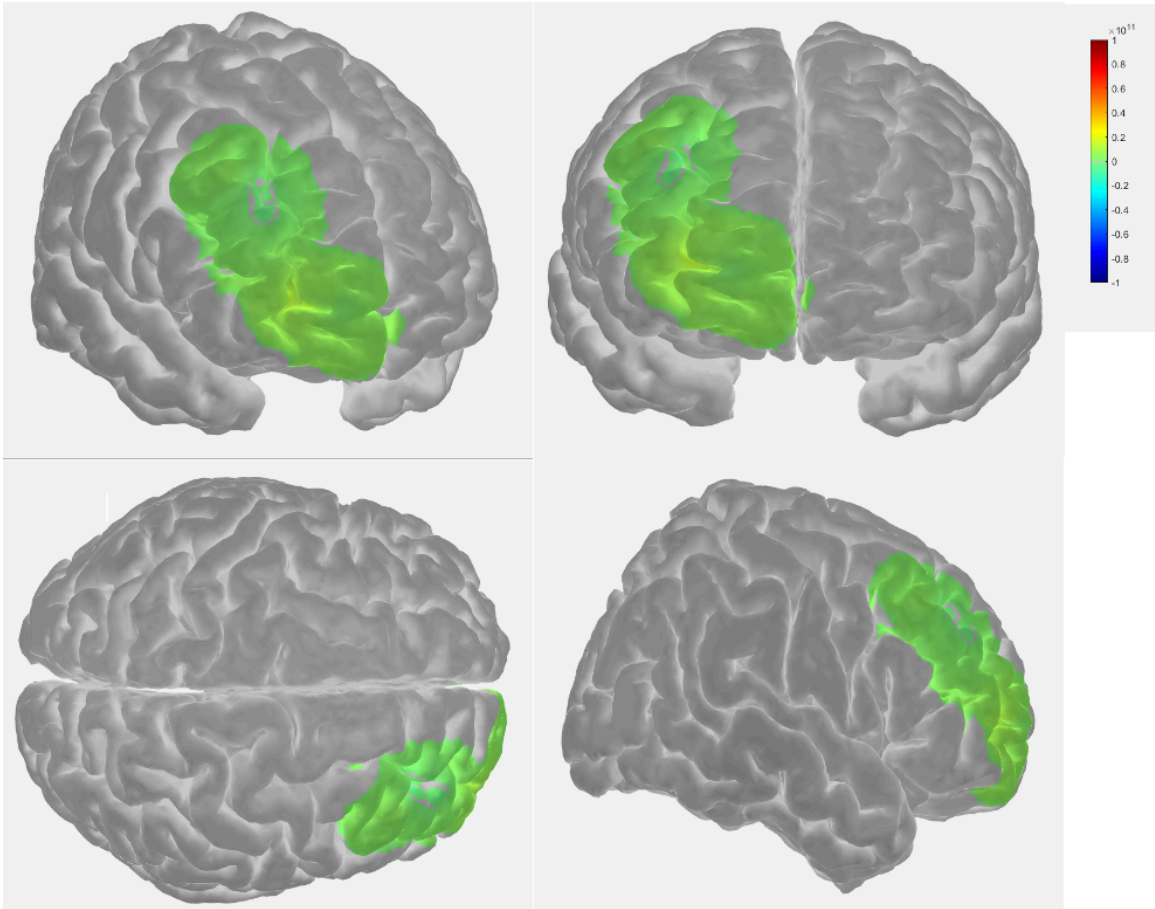participant does not click any key on the keyboard.

Figure 4. Default mode network activity in concussed participants during a rest task
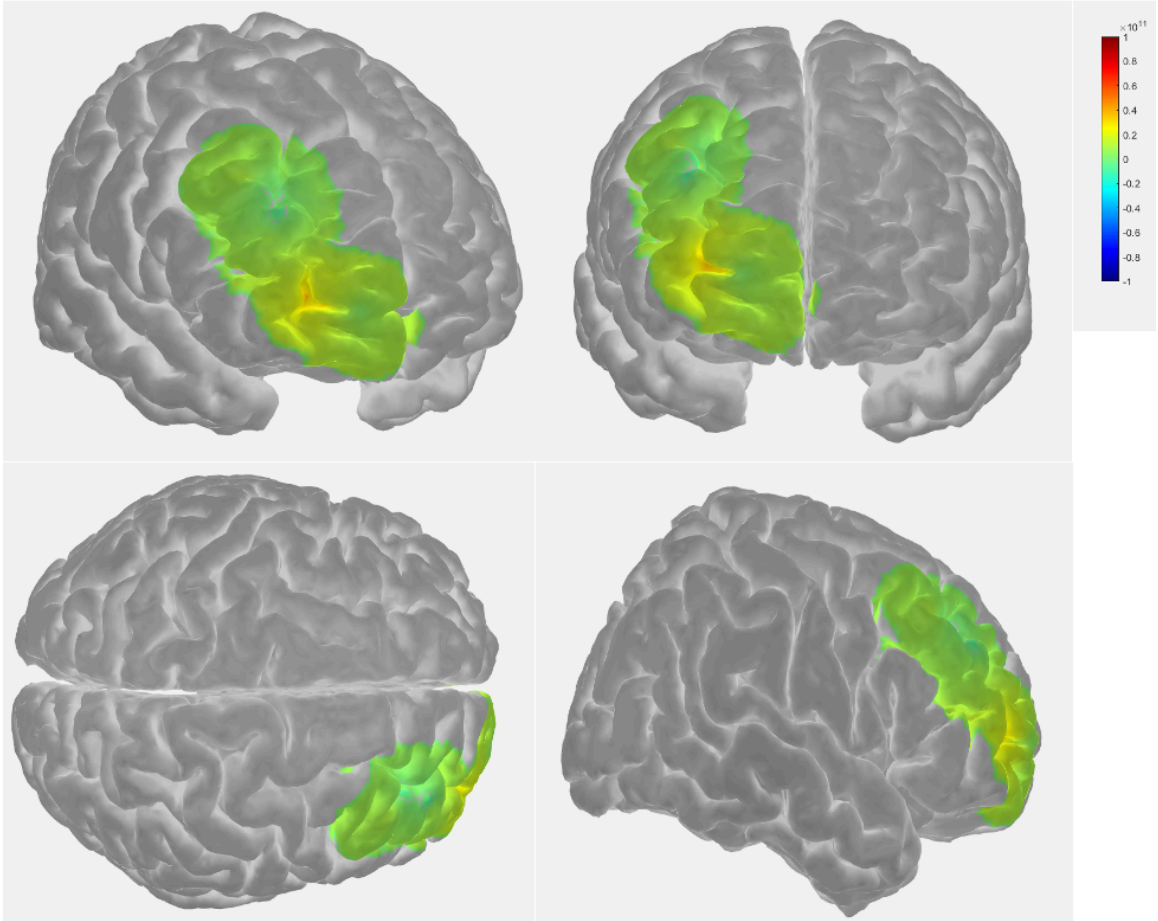
Figure 5. Default mode network activity in concussed participants during an active task
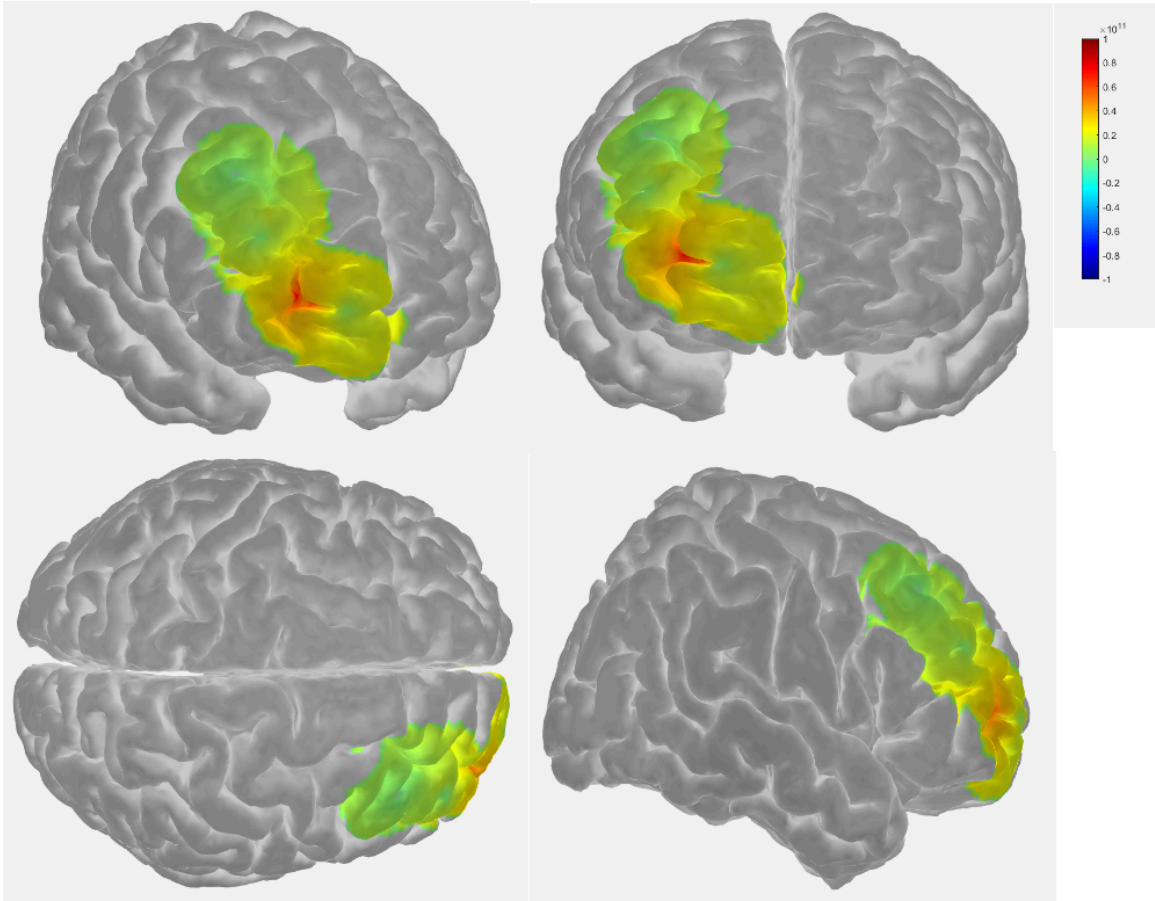
Figure 6. Default mode network activity in control participants during a rest task
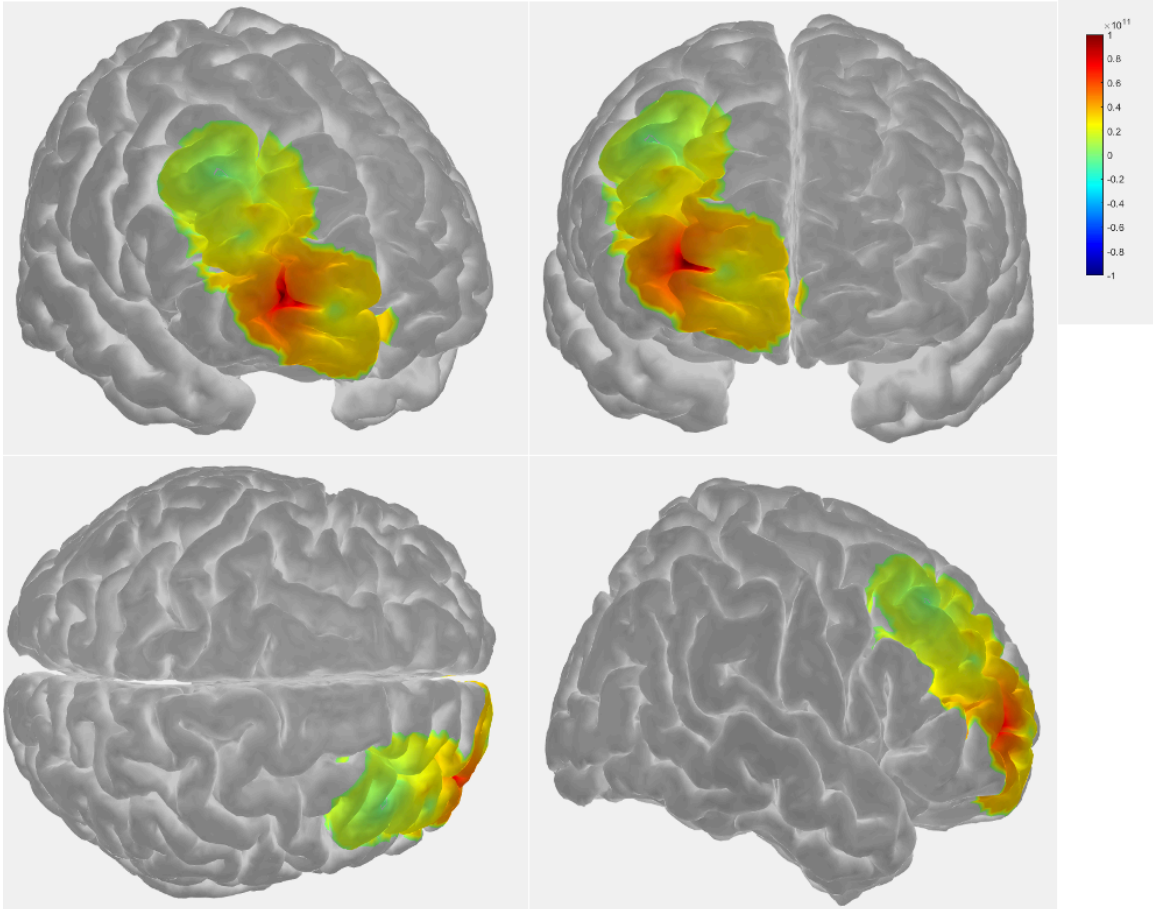
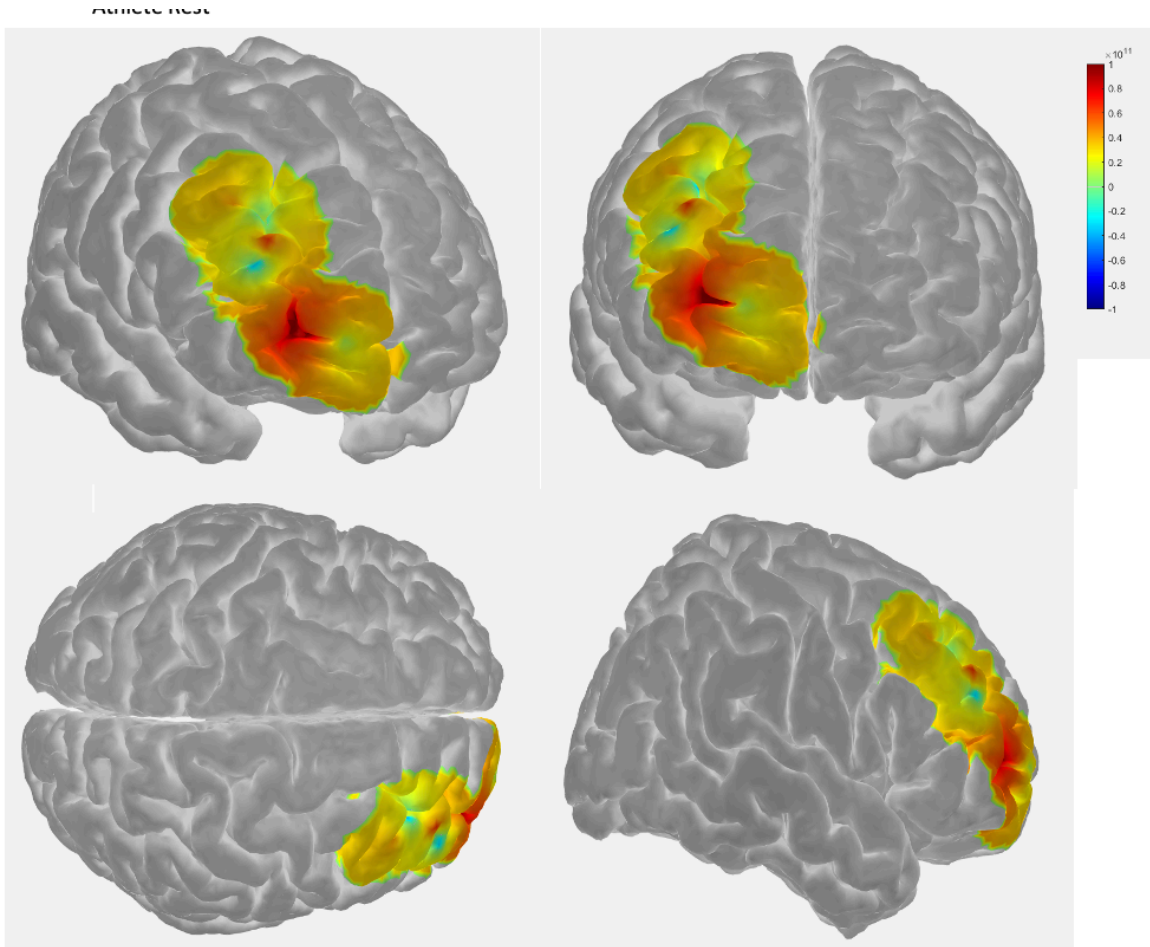*Figure 7.* Default mode network activity in control participants during an active task

Figure 8. Default mode network activity in control athletes during a rest task
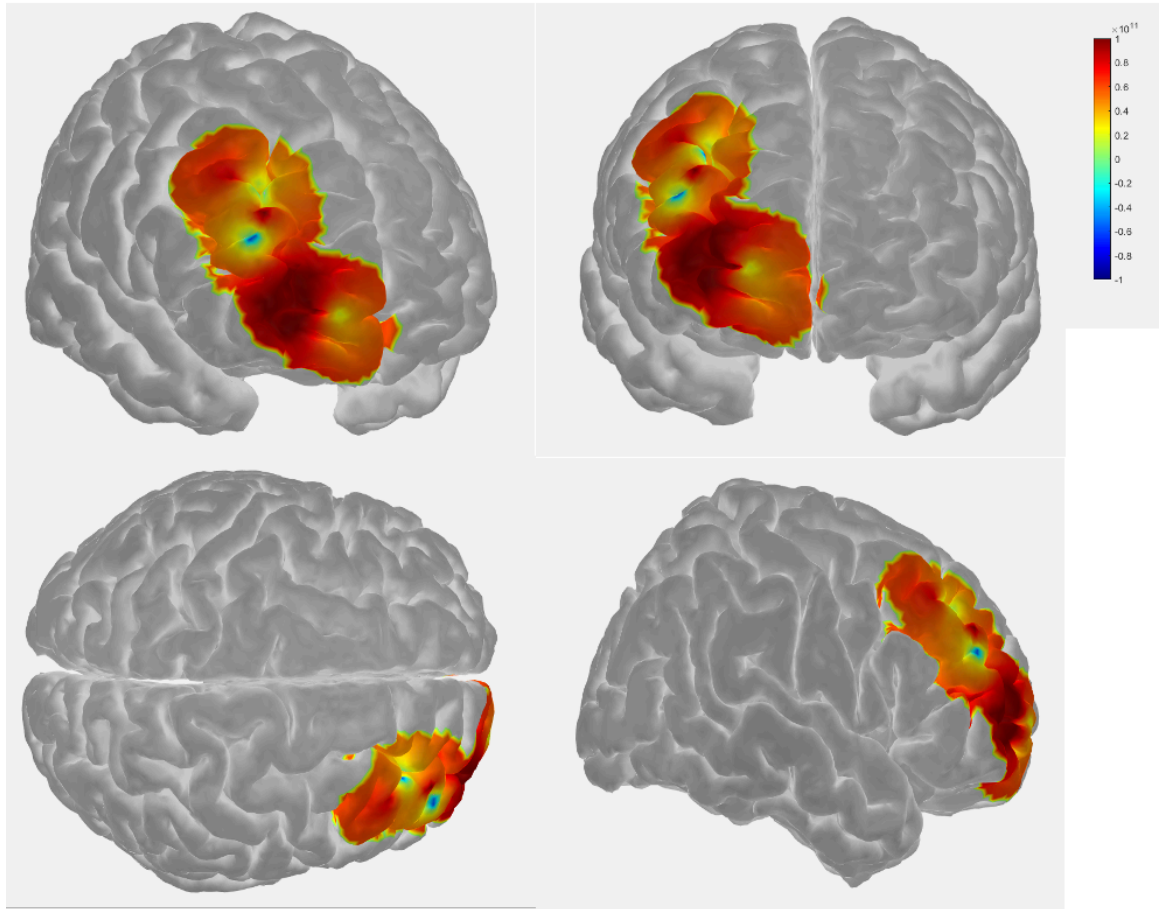
Figure 9. Default mode network activity in control athletes during an active task
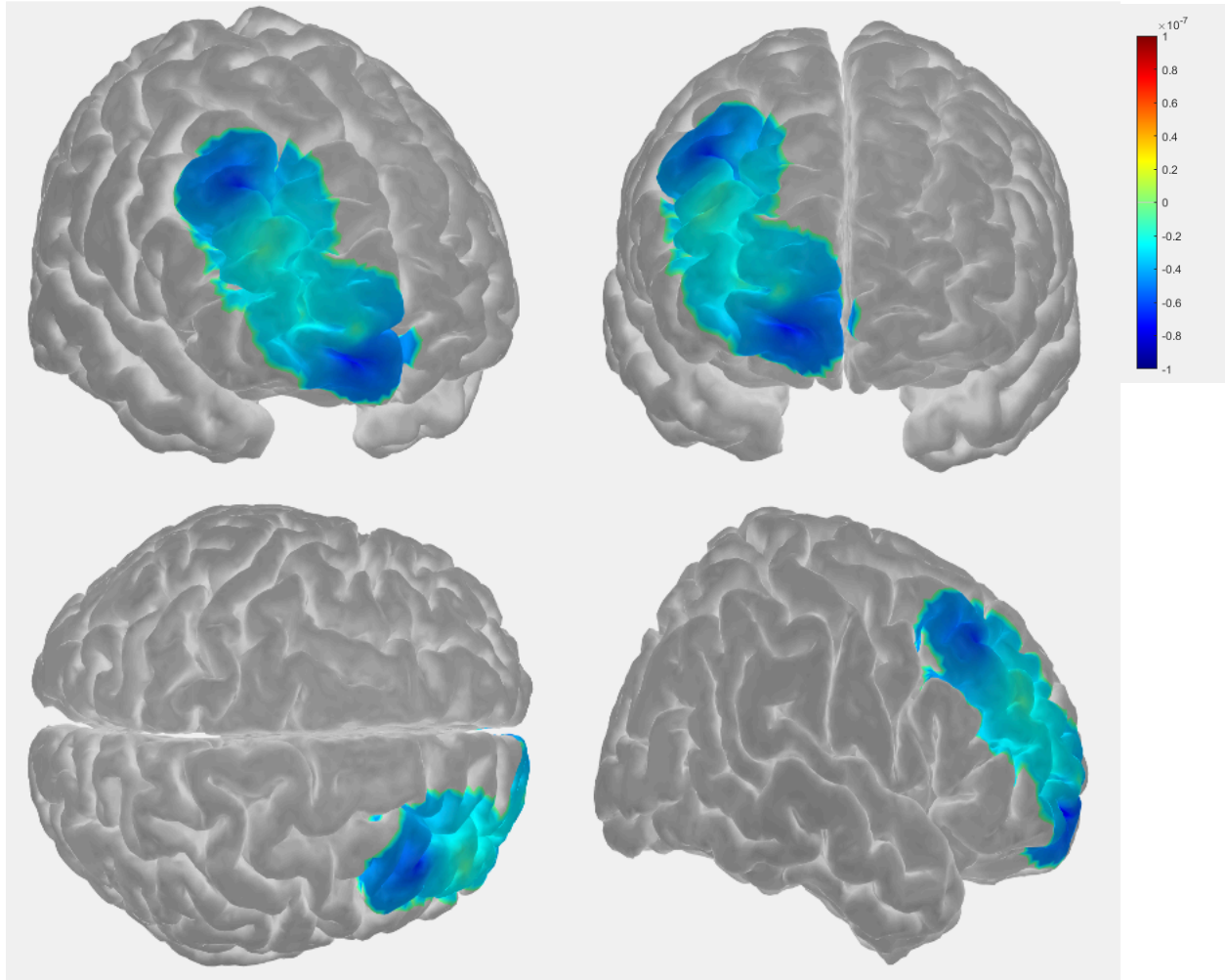
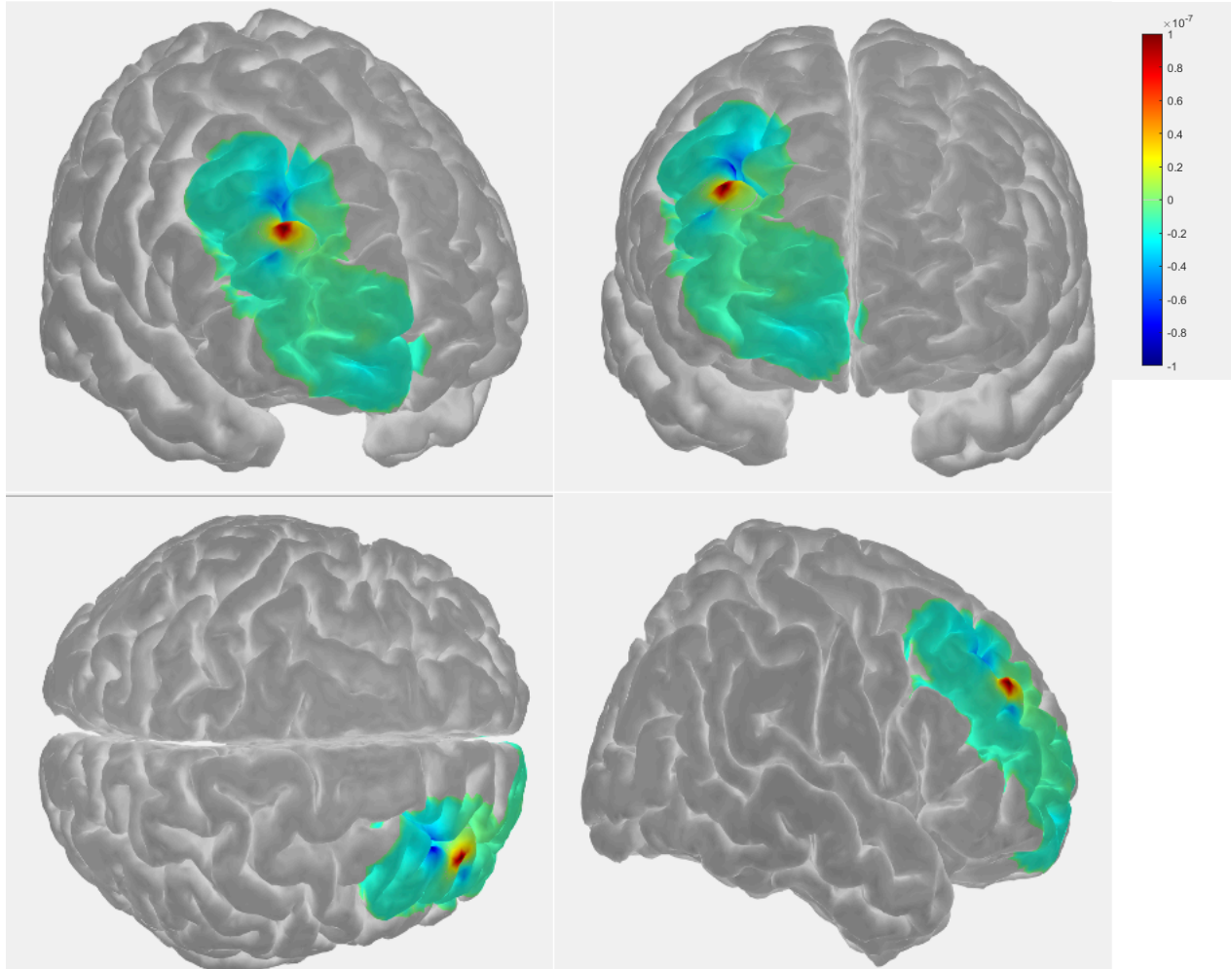*Figure 10.* Default mode network activity in female control participants during a rest task

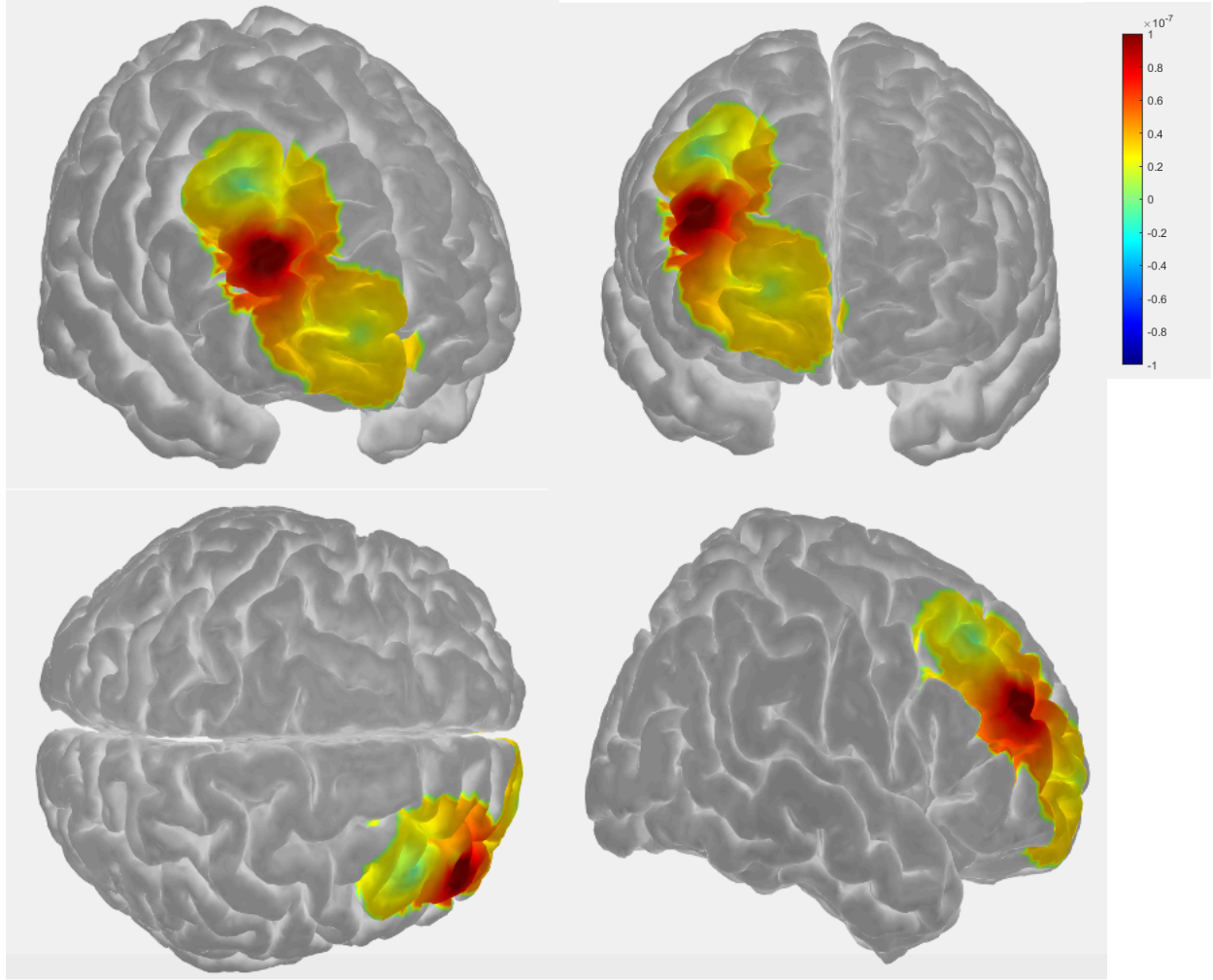*Figure 11.* Default mode network activity in male control participants during a rest task

Figure 12. Default mode network activity in female control participants during an active task
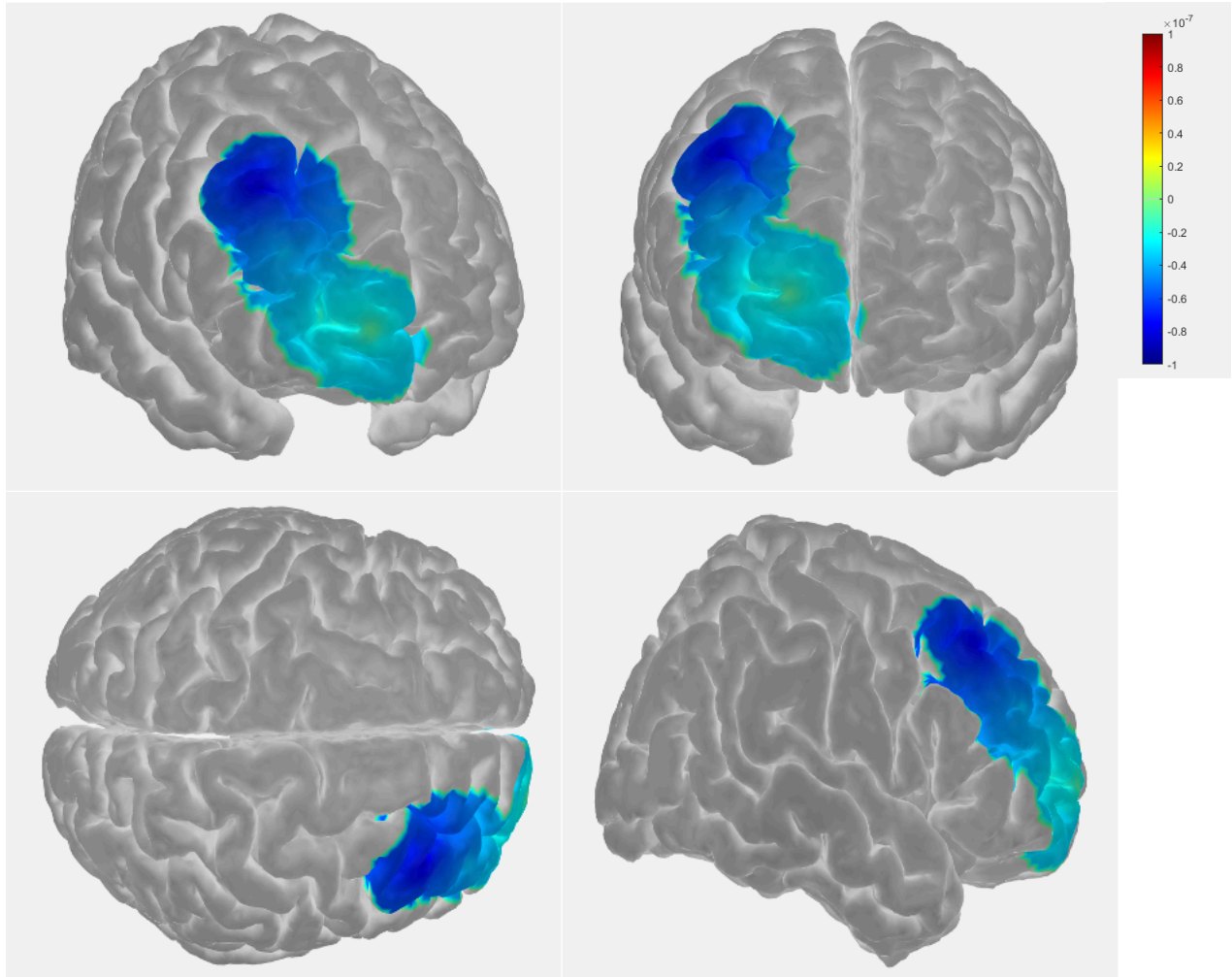
Figure 13. Default mode network activity in male control participants during an active task

Appendix C: Consent Forms

CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: Measuring Default Mode Network Activity using Functional Near Infrared Spectroscopy (Participant Pool)

You are asked to participate in a research study conducted by Brian Taylor and Dr. Christopher Abeare, from the Psychology Department at the University of Windsor. The results will be contributed to an undergraduate thesis.

If you have any questions or concerns about the research, please feel to contact Dr. Abeare or Brian Taylor .

PURPOSE OF THE STUDY

Brain activity is made up many different connections between cells. These connections allow for information to transmit quickly and efficiently throughout the brain to allow normal cognitive functioning. Areas that involve many connections working closely together are called neural networks. One neural network of current interest in neuroscience is called the default mode network.

The default mode network is active when individuals are at rest and not actively completing a task. This network is involved in processes such as self-reflection and planning. Past research suggests that activity in the default mode network can be affected by conditions such as concussions.

Activity of the default mode network can be observed using brain imaging techniques. The brain imaging technique used in this study is functional near infrared spectroscopy. This technique uses laser light to record brain activity. This study seeks to determine the effect of sports related concussion on activity of the default mode network.

PROCEDURES

If you volunteer to participate in this study, you will be asked to:
1. Give consent to participate in this study by reading this form.
2. Complete a scan using fNIRS that involves a 5 minute stop-signal task followed by a 3 minute rest. This task/break sequence is repeated 5 times.

You may also withdraw from the study at any point without penalty if you wish to quit.

In total, it is expected that this study will take less than 60 minutes to complete in total. (10 minutes for consent and setup and 40 minutes for the fNIRS scan)

Your answers will be kept confidential among the researchers. All data will be stored securely in a password-protected electronic database stored on an encrypted computer. While we must collect your email address for the sake of assigning you bonus points, your email address will not be attached to your data. A unique ID number will be assigned to your data. Only your responses and your ID number will be retained in this database. The database will be stored on an encrypted computer and secured when not in use.

POTENTIAL RISKS AND DISCOMFORTS

There are no known risks from participating in this study. On rare occasion people may experience mild emotional discomfort or mental fatigue during some of the tasks, but any negative reactions are expected to be mild and temporary. You will be wearing a neoprene headband that is used to measure brain activation. fNIRS is safe to use, however, the device uses class 2/3R lasers which can be harmful to one's eyes if mishandled. The researcher has certified training to handle the device and will give you clear, explicit instructions before the device is switched on. To set up the headband, the researchers will have to touch your head and hair. You will be asked to sit as still as possible while wearing the headband. Some people may feel discomfort from the headband or from sitting in one position for an extended period. It is possible that some people may experience mild and transient

anxiety, as the testing takes place in a small room with reduced lighting. If you feel uncomfortable answering any question or performing any task, you can choose to discontinue that section of the study without penalty. If you feel the need to talk to anyone about your feelings or wish to seek assistance, you will be provided a list of resources you can contact in the letter of explanation, at the end of the study.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

By participating in this study, you will receive course credit. You will also be exposed to how the research process works. Your participation in this study will also be important for the scientific community. We plan to publish the findings from this study, and hope that they inform on some of the effects of concussions.

COMPENSATION FOR PARTICIPATION

Participants will receive 1.5 bonus point for 60 minutes of participation toward the psychology participant pool, if registered in the pool and enrolled in one or more eligible courses. For students who do not complete the entire study, bonus points will be awarded corresponding to the amount of time spent (.5 credits = 30 minutes). This process is outlined in the Psychology Department Participant Pool handbook.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Your email address will be required for the purpose of assigning course credit; however, email addresses will not be linked with your responses.

Data collected during this study will be analysed and circulated (e.g. papers, presentations) on a group level only. No individual responses or patterns of responses will be shared.

PARTICIPATION AND WITHDRAWAL

Participation in this study is voluntary. Your choice of whether or not to participate will not affect your grades or academic status. If you decide to participate, you are free to withdraw your consent and to stop your participation at any time without penalty or loss of benefits to which you are allowed. You may also refuse to answer any tasks you don't want to complete and still remain in the study. Should you decide to withdraw from the study, compensation will be based on the time spent completing the study. Therefore, you will receive 0.5 points for every 30 minutes of participation. The investigator may withdraw you from this research if circumstances warrant it. You have the option of removing your data from the study until you leave the testing session. If you have any concerns regarding your data from the study, e-mail **Brian Taylor or Dr. Chris Abeare** After leaving the test session, you will not be able to withdraw your data as no personally-identifying information will be linked to your responses, and results will be stored anonymously and indefinitely.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

You may access the results of this study through the University of Windsor Research Ethics Board website:

Web address: http://www1.uwindsor.ca/reb/study-results/
Date when results are available: 21/04/01

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, N9B 3P4; Telephone: 519-253-3000, ext. 3948; e-mail: ethics@uwindsor.ca

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I understand the information provided for the study measuring activity of the default mode network using functional near infrared spectroscopy as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

_____
Name of Participant

_____   _____

Signature of Participant   Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

_____   _____

Signature of Investigator   Date

University of Windsor

CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: Measuring Default Mode Network Activity using Functional Near Infrared Spectroscopy (Sports Related Concussion)

You are asked to participate in a research study conducted by Brian Taylor and Dr. Christopher Abeare, from the Psychology Department at the University of Windsor. The results will be contributed to an undergraduate thesis.

If you have any questions or concerns about the research, please feel to contact Dr. Abeare or Brian Taylor

PURPOSE OF THE STUDY

    Brain activity is made up many different connections between cells. These connections allow for information to transmit quickly and efficiently throughout the brain to allow normal cognitive functioning. Areas that involve many connections working closely together are called neural networks. One neural network of current interest in neuroscience is called the default mode network.
    The default mode network is active when individuals are at rest and not actively completing a task. This network is involved in processes such as self-reflection and planning. Past research suggests that activity in the default mode network can be affected by conditions such as concussions.

    Activity of the default mode network can be observed using brain imaging techniques. The brain imaging technique used in this study is functional near infrared spectroscopy. This technique uses laser light to record brain activity. This study seeks to determine the effect of sports related concussion on activity of the default mode network.

PROCEDURES

If you volunteer to participate in this study, you will be asked to:
1. Give consent to participate in this study by reading this form.
2. Complete a scan using fNIRS that involves a 5 minute stop-signal task followed by a 3 minute rest. This task/break sequence is repeated 5 times.
You may also withdraw from the study at any point without penalty if you wish to quit.
In total, it is expected that this study will take less than 60 minutes to complete in total. (10 minutes for consent and setup and 40 minutes for the fNIRS scan)
Your answers will be kept confidential among the researchers. All data will be stored securely in a password-protected electronic database stored on an encrypted computer. While we must collect your email address for the sake of assigning you bonus points, your email address will not be attached to your data. A unique ID number will be assigned to your data. Only your responses and your ID number will be retained in this database. The database will be stored on an encrypted computer and secured when not in use.

POTENTIAL RISKS AND DISCOMFORTS

There are no known risks from participating in this study. On rare occasion people may experience mild emotional discomfort or mental fatigue during some of the tasks, but any negative reactions are expected to be mild and temporary. You will be wearing a neoprene headband that is used to measure brain activation. fNIRS is safe to use, however, the device uses class 2/3R lasers which can be harmful to one's eyes if mishandled. The researcher has certified training to handle the device and will give you clear, explicit instructions before the device is switched ons. To set up the headband, the researchers will have to touch your head and hair. You will be asked to sit as still as possible while wearing the headband. Some people may feel discomfort from the headband or from sitting in one position for an extended period. It is possible that some people may experience mild and transient anxiety, as the testing takes place in a small room with reduced lighting. If you feel uncomfortable answering any question or performing any task, you can choose to discontinue that section of the study without penalty. If you feel the need to talk to anyone about your feelings or wish to seek assistance, you will be provided a list of resources you can contact in the letter of explanation, at the end of the study.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

By participating in this study, you will receive course credit. You will also be exposed to how the research process works. Your participation in this study will also be important for the scientific community. We plan to publish the findings from this study, and hope that they inform on some of the effects of concussions.

COMPENSATION FOR PARTICIPATION

Participants will receive $20 for 60 minutes of participation in this study. For students who do not complete the entire study, compensation will be awarded corresponding to the amount of time spent ($10 = 30 minutes).

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Your email address will be required for the purpose of assigning course credit; however, email addresses will not be linked with your responses.

Data collected during this study will be analysed and circulated (e.g. papers, presentations) on a group level only. No individual responses or patterns of responses will be shared. Data from this research will not be deidentified in order to be matched to your SRCC data.

PARTICIPATION AND WITHDRAWAL

Participation in this study is voluntary. Your choice of whether or not to participate will not affect your grades or academic status. If you decide to participate, you are free to withdraw your consent and to stop your participation at any time without penalty or loss of benefits to which you are allowed. You may also refuse to answer any tasks you don't want to complete and still remain in the study. Should you decide to withdraw from the study, compensation will be based on the time spent completing the study. Therefore, you will receive 0.5 points for every 30 minutes of participation. The investigator may withdraw you from this research if circumstances warrant it. You have the option of removing your data from the study until you leave the testing session. If you have any concerns regarding your data from the study, e-mail **Brian Taylor or Dr. Chris Abeare.** After leaving the test session, you will not be able to withdraw your data as no personally-identifying information will be linked to your responses, and results will be stored anonymously and indefinitely.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

You may access the results of this study through the University of Windsor Research Ethics Board website:

Web address: http://www1.uwindsor.ca/reb/study-results/
Date when results are available: 21/04/01

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

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SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I understand the information provided for the study measuring activity of the default mode network using functional near infrared spectroscopy as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

_____
Name of Participant

_____   _____
Signature of Participant   Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

_____   _____
Signature of Investigator   Date

Appendix D: Recruitment Forms

Title: Measuring Default Mode Network Activity using Functional Near Infrared
      Spectroscopy

Researchers: Brian Taylor , Dr. Christopher Abeare

Duration: 60 minutes

Compensation: $50

Description: Participants will complete an fNIRS scan of the default mode network during both
non-active relaxation and a simple cognitive task.

The risks of participating are, at most, minimal. This study will take no more than 60 minutes of
your time, and all athletes in the SRCC can complete this studying within 3 weeks of concussion,
following clinical evaluation.

Title: Measuring Default Mode Network Activity using Functional Near Infrared
      Spectroscopy

Researchers: Brian Taylor , Dr. Christopher Abeare

Duration: 60 minutes

Compensation: $20

Brain activity is made up many different connections between cells. Areas that involve many connections working
closely together are called neural networks. One neural network of current interest in neuroscience is called the
default mode network. The default mode network is active when individuals are at rest and not actively completing a
task. This network is involved in processes such as self-reflection and planning. Past research suggests that activity
in the default mode network can be affected by conditions such as concussions. Activity of the default mode
network can be observed using brain imaging techniques. The brain imaging technique used in this study is
functional near infrared spectroscopy (fNIRS). This technique uses laser light to record brain activity. Participants
will complete a fNIRS scan of the default mode network during both non-active relaxation and a simple cognitive
task to assess activity.

The risks of participating are, at most, minimal. This study will take no more than 60 minutes of your time and is
worth $20.

**Please refrain from intensive exercise, smoking cigarettes and/or marijuana, and consuming caffeinated
and/or alcoholic beverages for 8 hours proceeding testing sessions. Come to the session with no makeup or
concealer on your forehead.**

To set up the device, the researcher will have to touch your head and part your hair to provide a clear and
unobstructed view of the scalp. You will be asked to undo any hairstyles (braids, buns, ponytails, etc.) so that the
device can be properly mounted. Should you have concerns about how your hair and/or hairstyle may impact the

researcher's ability to gain an obstructed view of your scalp, please contact the researcher of the fNIRS Lab Coordinator with any questions.

Title: Measuring Default Mode Network Activity using Functional Near Infrared
                   Spectroscopy

Researchers: Brian Taylor , Dr. Christopher Abeare

Duration: 60 minutes

Compensation: 1.5 points

Brain activity is made up many different connections between cells. Areas that involve many connections working closely together are called neural networks. One neural network of current interest in neuroscience is called the default mode network. The default mode network is active when individuals are at rest and not actively completing a task. This network is involved in processes such as self-reflection and planning. Past research suggests that activity in the default mode network can be affected by conditions such as concussions. Activity of the default mode network can be observed using brain imaging techniques. The brain imaging technique used in this study is functional near infrared spectroscopy (fNIRS). This technique uses laser light to record brain activity. Participants will complete a fNIRS scan of the default mode network during both non-active relaxation and a simple cognitive task to assess activity.

The risks of participating are, at most, minimal. This study will take no more than 60 minutes of your time and is worth 1.5 points.

Please refrain from intensive exercise, smoking cigarettes and/or marijuana, and consuming caffeinated and/or alcoholic beverages for 8 hours proceeding testing sessions. Come to the session with no makeup or concealer on your forehead.

To set up the device, the researcher will have to touch your head and part your hair to provide a clear and unobstructed view of the scalp. You will be asked to undo any hairstyles (braids, buns, ponytails, etc.) so that the device can be properly mounted. Should you have concerns about how your hair and/or hairstyle may impact the researcher's ability to gain an obstructed view of your scalp, please contact the researcher of the fNIRS Lab Coordinator with any questions.

Appendix E: fNIRS Prescreening Information

Prescreen Questionnaire

1. Age:
2. Are you able to use a mouse and keyboard?
3. Have you ever had a severe head injury where you lost consciousness or required accommodations for more than one month?
4. Have you ever been diagnosed with a hearing or visual impairment that would affect your ability to hear or see the tasks required for this testing session?
5. Is English your first language? If no, are you fluent?
6. People with a history of learning and attention problems sometimes perceive information more slowly than their peers. Have you ever been diagnosed with ADHD or a learning disorder?
7. Have you ever been diagnosed with a neurological disorder (e.g., Parkinson's, cerebral palsy)
8. How many hours of sleep did you get last night?
9. Do you play on a varsity sports team? If yes which one?
10. If applicable:
a) What date did you start your last period?
b) Do you have a regular cycle (21-35 days consistently for at least the past 3 months)?

Day of Screener (administered at testing session)

Have you in the past 8 hours (circle your response):

1. Drank coffee/caffeinated beverages?	Yes	No
2. Smoked cigarettes?	Yes	No
3. Smoked marijuana?	Yes	No
4. Exercised?	Yes	No
5. Drank alcohol?	Yes	No

*If yes to any of the above, how long ago?

coffee/caffeinated beverages

Cigarettes

Marijuana

Exercise

Alcohol

PAST MEDICAL HISTORY

Other than the most recent brain injury, do you have a history of? (Circle) TBI   Stroke   TIAs   Dementia   Brain tumour Seizures   Multiple Sclerosis   Headaches   Migraines Insomnia

MENTAL HEALTH HISTORY

Before your brain injury were you ever diagnosed with or treated for: Anxiety   Depression   Panic Attacks   Schizophrenia   Bipolar   Alcoholism Substance abuse   Sleep difficulties Describe onset, duration, and treatment: **After your brain injury were you ever diagnosed with or treated for:** Anxiety   Depression   Panic Attacks   Schizophrenia   Bipolar   Alcoholism Substance use   Sleep difficulties Describe onset, duration, and treatment:

Ever been in a psychiatric hospital	Yes No When?_____
Currently take medications to calm your nerves or help your mood?	Yes No How long?_____ What medication? _____

VITA AUCTORIS

NAME: Brian Taylor

PLACE OF BIRTH: Windsor, ON

YEAR OF BIRTH: 1997

EDUCATION: St Anne Catholic High School, Lakeshore, ON, 2015

                   University of Windsor, B.Sc., Windsor, ON, 2019