AN EXAMINATION OF CONCEPTUAL KNOWLEDGE USING NEAR-INFRARED SPECTROSCOPY AND ELECTROENCEPHALOGRAPHY

by

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Abstract

Traditionally, models of conceptual knowledge have relied upon amodal theories that largely overlook how environmental stimuli are converted into amodal representations and how perceptions reactivate these representations and translate them back into subjective modal experiences. Developed more recently, grounded cognition theories propose that physical experiences and conceptual knowledge rely, at least in part, on the same brain regions. Thus, conceptual knowledge is hypothesized to be experienced through the reactivation of the same brain regions that are activated during physical experiences with the environment. Furthermore, if these grounded hypotheses are correct, researchers should be able to observe predictable influences of grounded information on brain activity as well as participant response latencies and accuracy in experimental conditions.

To this end, three experiments were conducted testing these hypotheses using semantic categorization tasks while simultaneous recordings were taken using functional near infrared spectroscopy (NIRS) and electroencephalography. It was hypothesized that the influence of automatically reactivated grounded information would be facilitatory (i.e., resulting in faster and more accurate responses for semantically richer words) when it was task congruent, but would be inhibitory (i.e., resulting in slower and less accurate responses for semantically richer words) when it was task incongruent, thus illustrating the automatic simulation of grounded information in the processing and retrieval of conceptual knowledge.

NIRS was employed to monitor event-related patterns of prefrontal cortex (PFC) hemodynamics associated with these tasks. It was hypothesized that trials with high levels of task-relevant semantic information would be discernably different than those with low levels or those trials high in task-incongruent information. That is, given the high levels of task-relevant

semantic information, these trials should be comparatively easier, thus requiring less activity in the PFC, resulting in less pronounced hemodynamic responses. Electroencephalography was employed to monitor the full-scalp event-related patterns of brain activity associated with the experimental tasks. It was hypothesized that event-related potential deflections and scalp topography would be able to discern qualitatively and quantitatively different patterns of activity as a function of the amount and relevance of grounded information obtained through physical and emotional experiences with the word stimuli's referents.

The behavioural, accuracy, and electroencephalography data generally support these hypotheses. When a stimulus's grounded information is high and task relevant, participants responded more quickly and accurately, and had discernably different patterns of brain activity than when a stimulus's grounded information was low and task relevant. When a stimulus's grounded information was high and task-irrelevant, participants were slower and less accurate, and exhibited patterns of brain activity that reflected both the additional semantic information and the additional processing necessary to reconcile the task incongruence. Unfortunately, data obtained from NIRS failed to illustrate meaningful condition differences. Possible reasons for this are discussed in detail in Chapter 3.

Collectively, the data presented in this dissertation serve to advance and extend the claims made by grounded cognition theorists by illustrating the automatic simulation of information obtained through interactions with the environment. Further research is required to extend this work to other brain regions and to develop NIRS methods that can address these research questions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

[x]	concentration of x
ANOVA	analysis of variance
BOI	body-object interaction
BOLD	blood-oxygen level dependent
CW	continuous wave
DL-PFC	dorsolateral prefrontal cortex
EE	emotion experience
EEG	electroencephalography
EMG	electromyograph
ERP	event related potential
fMRI	functional magnetic resonance imaging
fNIRS	functional near infrared spectroscopy
FPC	frontopolar cortex
HHb	deoxygenated hemoglobin
IFC	inferior frontal cortex
ITI	inter-trial interval
LDT	lexical decision task
LPC	late positive component
O_2Hb	oxygenated hemoglobin
OF-PFC	orbitofrontal prefrontal cortex
PFC	prefrontal cortex
PSS	perceptual symbol systems

Sat%	regional tissue oxygen saturation
SCT	semantic categorization task
SE	standard error
THb	total hemoglobin
VM-PFC	ventromedial prefrontal cortex

DEDICATION

I have such an amazing network of loving and supportive friends, family, and colleagues without whom this work would never have been completed. My mother, who forgives my every trespass and thinks the world of me regardless of my antics. My brother, who sees the best in me despite knowing better. My beautiful wife, who believes in me even when I am at my worst and supports me in every way. This work is dedicated to you. To the rest of my friends and family who saw me through this process: you may never know what your support meant to me. To all of you: thank you for believing in me.

CHAPTER 1: INTRODUCTION

The four word categorization experiments presented here were conducted in an effort to address questions surrounding the nature of human conceptual knowledge. Two neuroimaging technologies (electroencephalography and near-infrared spectroscopy; EEG and NIRS) were employed concurrently with behavioural (response latency and response accuracy) measurements to contribute to this growing body of research. A grounded cognition perspective was adopted in the formation and interpretation of the hypotheses in each experiment. Collectively, the data presented in Chapters 3 and 4 provide evidence that the processing of conceptual information involves the automatic reactivation of semantic information obtained from physical and emotional experiences with one's environment. Importantly, these data (see Chapter 3, Experiment 3) demonstrate that reactivation of grounded knowledge is automatic even when it is not congruent with task demands. Additionally, the data acquisition and analysis techniques employed in the research presented demonstrate a new and comparatively accessible methodology to address fundamental questions in cognitive psychology. In sum, the data presented in the following chapters serve as a contribution to and extension of grounded cognition hypotheses as well as a novel method for the analysis and presentation of psychophysiological data.

One of the key predictions made by grounded cognition theory is that the neurological basis of conceptual knowledge should vary as a function of the nature of the knowledge (Barsalou, 1999; Pecher et al., 2011; Pulvermuller, 2013). This prediction is the result of the grounded hypothesis that conceptual knowledge is experienced through the partial reactivation of at least some of the same sensory, motor, and emotion brain regions that were active during the acquisition of that knowledge (Barsalou, 1999). This hypothesis is based largely on Barsalou's

(1999) Perceptual Symbol Systems (PSS) framework. The PSS proposes that conceptual knowledge is formed and represented symbolically in sensory, motor, and emotion brain regions during experiences with one's environment. Importantly, different concepts should be realized in the brain differentially in both qualitative and quantitative manners. For example, while the concepts of *flashlight* and *fork* may be primarily represented neurologically in visual and motor brain regions, one may predict that individuals would have more experience with forks than with flashlights. As a result, one may predict that the neurological activation of concepts that have greater amounts of semantic information obtained through physical experiences with the words' referents would have greater levels of activity in the implicated motor regions. Conversely, while the concepts of *fork* and *sunset* may both be represented neurologically in visual brain regions, *sunset* would not have any motor representation due to individuals having no bodily interactions with sunsets. As a result, one may predict that the characteristic patterns of neuronal activity associated with processing such concepts would be qualitatively different. A more thorough exploration of the theoretical basis for this project can be found in Chapter 2.

Across four experiments, participants' lexical semantic knowledge was activated through one lexical decision task (LDT) and three semantic categorization tasks (SCT). In the LDT, participants are presented with a letter string and are to identify if the string spells a real word. In principle, one need only recognize the correct spelling of a word to complete this task successfully. In a SCT, participants are presented with a real word and are asked to make a categorical decision about that word (e.g., Is this word a concrete noun?: Newcombe et al., 2012; Is this word easily imageable?: Hargreaves et al., 2012; Is this a verb?: Noguchi et al., 2002). To successfully complete a SCT trial, participants must activate their conceptual representations of a presented word and compare representation against current task demands. By manipulating the semantic dimensions along which stimuli vary, researchers can experimentally observe the role of that dimension on task completion. In the experiments presented in Chapters 3 and 4, the stimuli varied along the dimensions of body-object interaction (BOI) ratings (i.e., a measure of the ease of bodily interacting with a word's referent) and emotional experience (EE; i.e., a measure of the ease by which a word evokes emotion information; Newcombe et al., 2012). The effect of these variables on conceptual processing were measured behaviourally through analyses of response latencies and accuracy in the LDT and SCTs. Detailed predictions and more thorough reviews of these semantic variables are found in Chapters 2, 3, and 4.

To measure the qualitative and quantitative processing differences of various concepts, two neuroimaging techniques were employed concurrently. First, near-infrared spectroscopy (NIRS) was used to measure hemodynamic activity in the prefrontal cortex (PFC). This technology works by emitting light in the near-infrared spectrum into target tissues and recording the amount and wavelength of light that exits nearby tissue (Sato et al., 2013). This technique is effective due to the fact that oxygenated and deoxygenated hemoglobin preferentially absorb different wavelengths of near-infrared light. Thus, by emitting two or more wavelengths of light into tissue of interest and observing the comparative amounts of each wavelength that escape, inferences can be made about the composition of regional blood flow (Elwell & Hebden, 1999). Such data is informative in cognitive research due to regional perfusion overshoot (Verner et al., 2013). That is, when neurons fire, they consume resources such as glucose from the regional blood supply. When compensating for this resource depletion, oxygen-rich arterial blood fresh blood is delivered to the area. As such, researchers can make inferences about task-dependent neuronal processing as a function of changes in regional hemoglobin oxygenation. A more thorough review of this technology and hypotheses specific to NIRS are presented in Chapter 3.

When neurons fire, there is a small voltage discharge that is associated with the action potential. Electroencephalography (EEG) was used in the experiments in Chapter 4 to detect these polarity changes at the scalp. EEG, as a technology has been long validated for its ability to show task- and condition-dependent regional and amplitude differences in electrical brain activity (Khrizman, 1973). EEG devices can record upwards of 1000 times per second, making it an ideal functional neuroimaging technique for observing brain activity that is uniquely associated with a single trial's brain activity (event-related potentials; ERP). In the four experiments presented in the subsequent chapters, full-scalp ERPs were recorded concurrently with NIRS recordings because the two technologies are compatible; NIRS uses fiber-optic cables to carry signals and, as a result, does not interfere with the sensitive electrical recordings made by EEG devices. Particular ERP components of interest and specific hypotheses related to the ERP data are found in Chapter 4.

Broadly speaking, the general hypotheses across all experiments are as follows. First, response latencies will be shorter and more accurate for stimuli with high levels of grounded semantic richness (see Chapter 2) except when the nature of the grounded semantic richness is incongruent with task demands (i.e., Chapter 3 – Experiment 3). Second, NIRS will reveal greater amounts of cerebral hemoglobin oxygenation and total saturation accompanied with lower amounts of deoxygenated hemoglobin (see Chapter 3) for more effortful trials. That is, for those trials that are low in task-relevant grounded semantic richness or for those trials high in task-irrelevant grounded semantic richness. Finally, EEG will reveal a) quantitative differences insofar as various ERP components directly reflect cognitive effort (i.e., low grounded semantic richness trials will be harder to process) and b) qualitative differences insofar as the scalp distribution of various ERP components will differ as a function of the nature of task demands and the manipulated dimension of grounded semantic richness. More thorough and specific predictions can be found in Chapter 3 (behavioural and NIRS) and Chapter 4 (EEG).

To demonstrate the degree to which the physiological hypotheses are supported by the data, a novel Bayesian approach is introduced in Chapters 3 and 4. Specifically, difference waves were calculated across time between high- and low-grounded semantic richness trials and then displayed with Bayesian 99% credible intervals. This is an application of Nathoo et al.'s (2018) validation of this technique to calculate variance across time and space (the authors originally used this technique to plot reach and grasp trajectories). This technique is applicable to high-density data arrays without incurring the risk of a Type I error as is typical in frequentist analyses. By displaying difference waves with Bayesian credible intervals, a viewer is able to simply look at the data and observe when, across time, non-zero condition differences occur. The data can then be interpreted in relation to the original physiological waveform components. This is particularly well suited to the current program of research due to the many different dimensions along which psychophysiological data can vary (see Chapter 2 for further discussion).

In sum, the data presented in the chapters that follow stand as an application and extension of grounded cognition hypotheses with regard to semantic processing of conceptual knowledge. Further, neurological predictions are tested through concurrent applications of two different neuroimaging technologies and analyzed with a novel methodology. Collectively, these experiments will contribute to and strengthen grounded interpretations of human conceptual knowledge while illustrating the neurological correlates thereof using non-invasive technologies and introduce a sophisticated and accessible method for interpreting the data.

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CHAPTER 2:

Investigating the Neurological Correlates of Grounded Conceptual Knowledge

Classical accounts of cognition claim that knowledge gained through sensory, motor, and emotional experience is translated into cognitive representations that are amodal, and hence stripped of the associated features of the original lived experience (e.g., the shape or colour of what was visually observed) (Fodor, 1983). In other words, conceptual knowledge involves the transformation of sensorimotor and emotion information into a form of abstract cognitive representational code comparable to a computer language (Niedenthal, et al., 2005). Amodal accounts of cognition have, however, been challenged as being more descriptive than predictive (see Barsalou, 1999). Amodal theories are likely sufficient for describing patterns of observed data from conceptual processing research and have guided the development of cognitive models that identify and quantify key factors in semantic processing, such as a word's age of acquisition (e.g., Dehaene, 2011; Machery, 2016). However, it has been argued that amodal theories of cognition have failed to explain how sensorimotor and emotion information is transformed into amodal cognitive representations, how external stimuli passively prompt retrieval of these representations, and how they are transformed back to and experienced as subjective experiences (Glenberg, et al., 2000); and that amodal theories do not offer an explanation of how or why humans evolved amodal representation processes. This issue is frequently discussed as the grounding problem (e.g., Harnad, 2003; Pecher & Zwaan, 2005), which is the debate of how symbolic representations of conceptual knowledge are mapped from the environment, into mental symbolic representation, and then from these representations back into a state with references to the real world. Without verifiable cognitive mechanisms capable of bridging one's multimodal interactions with the physical environment (arising through sensory, motor, and emotion experience) and the cognitive processing thereof, it is argued that classical cognitive theories have implicit shortcomings (Johnson, 2017).

Barsalou (1999) proposed an influential grounded cognition framework that he called Perceptual Symbol Systems (PSS). According to this framework, partially reactivated neural networks in sensorimotor and emotion regions, or "simulations", are thought of as perceptual symbols. From this perspective, unconscious automatic processing (e.g., sensation and perception) and conscious, effortful processing (e.g., decision making and selective attention) both rely, at least partially, on the same brain regions. By accepting this proposition, proponents of grounded cognition have alleviated the need to account for the transformation of sensorimotor and emotion representations to amodal cognitive representations that putatively represent previous experiences; the brain forms, stores, reactivates, and combines these perceptual symbols to accomplish dynamic cognitive processing that allows for efficient interactions between humans and their environments.

Barsalou's (1999) PSS framework further proposes that the sensory, motor, and emotion networks formed through one's physical interactions with the environment can serve symbolically in cognition. Take, for example, one's conceptual knowledge of *dog*. Every time one perceives a dog, there are corresponding patterns of neural activation (e.g., brain regions responsible for the sight of the dog's shape and colour, the smell of a dog, the feeling of a dog's fur, etc.). A subset of these experiences is stored as the perceptual symbol for *dog*. Langacker (1987) described this process as superimposing transparencies atop one another: anything common to all or most transparencies will remain clear, whereas anything unique to a single transparency will become blurred and indistinct over time. Across one's life, there will be commonalities between these separate *dog* experiences. As a result, the neural activations that are common across all such experiences will develop stronger interconnections, thereby producing a reliable sense of meaning for one's concept of *dog*.

Furthermore, Barsalou's PSS framework allows for perceptual symbols to be recombined dynamically. For example, in addition to *dog* one may develop a concept of *purple* resulting from all of one's perceptual and physical experiences with purple stimuli. Although one may not ever actually perceive a purple dog, by activating both *dog* and *purple* perceptual symbols concurrently one can conceptualize a *purple dog*. By experiencing the activation of both *purple* and *dog* perceptual symbols together, one may form a connection between the two concepts, creating a new perceptual symbol without direct perceptual or physical experience with its referent. Cognitive activity, according to the PSS framework, can form new perceptual symbols during offline cognitive processing.

The PSS framework is compatible with other grounded frameworks of cognition. For example, Anderson et al. (2013) propose that higher cognitive operations are *softly assembled*. That is, cognitive operations are not discrete entities. Rather, cognitive operations such as memory are realized simultaneously across multiple brain regions with no discrete beginning, end, or location. Cognition from this perspective is a dynamic process that must always be understood contextually as an interaction between one's history, context, and current task demands. If correct, this framework would imply that, while there may be neurological commonalities across multiple instances of the same process, there is no a priori reason for neuropsychological researchers to study discrete temporal epochs or scalp topographies associated with particular processes. Together, these frameworks suggest that conceptual knowledge is assembled contextually and dynamically. The PSS framework is, however, comparatively specific in its predictions. A perceptual symbol cannot truly exist if it is spontaneously, dynamically, and differentially formed for each activation. Neuroimaging researchers could dissociate between these predictions by examining the stability in patterns of activation across trials and across experimental replications.

Pulvermuller (2013) has asserted that any theory that relies on amodal cognitive representations is fundamentally incomplete and exists in defiance of modern evidence. Recently, theorists have begun to accept that cognition's primary purpose is to guide interactions between one's body and environment (Anderson et al., 2013). In this sense, cognition is best understood as the product of evolution. Higher cognition must be thought of as the product of simpler systems that evolved earlier (Pecher et al., 2011). Evolution does not lead to the creation new brain structures without building on pre-existing structures, so it seems reasonable to conclude that higher level cognitive processes are built upon operations of sensation and action (Pecher et al., 2011). The most accurate cognitive theories are, as a result, likely to be those that are heavily reliant on sensation, perception, and action to explain cognitive processes.

Specifically, human cognition would be the product of evolutionary adaptations that improved reproductive success by increasing the efficiency of environmental processing. Sensation and action would evolve first, providing the basis for higher cognition (e.g., selective attention, memory, decision making, etc.). All subsequent cognitive processes would rely on this foundation as they developed. This idea is in direct contrast with the classical cognition idea that there is no such relationship between cognition and the environment (Meteyard et al., 2012). The theoretical position that many, if not all, cognitive processes are dependent upon and resultant of the interactions between one's body and environment is known variously as embodied or grounded cognition (Barsalou, 1999).

From a grounded cognition perspective, many cognitive processes rely on sensory and motor brain regions (e.g., Barrett, & Lindquist, 2008; Barsalou, 1999; Caligiore & Fischer, 2012); and some theorists even argue that all cognitive processes rely on such brain regions (e.g., Chimero, 2013; Favela, 2014). The underlying idea is that one's conceptual knowledge is largely due to one's previous sensorimotor interactions with the environment (Barsalou, 1999). While humans interact with the environment, a subset of the sensory and motor cortices that are active during perception and action begin to form networks due to co-occurrence effects (Hebb, 1949). Offline cognition (i.e., mental processing of information that is not immediately necessary for action, like reading written language), it is argued, is possible through subsequent partial reactivations of these networks (Siakaluk et al., 2008; Barsalou, 2016; Barsalou, 1999, calls these networks 'simulators', and partial reactivation 'simulations'). That is, one's thoughts and memories of an experience *are*, at least partially, represented neurologically in the same brain regions that are active during that experience (for example, see Hargreaves et al., 2012).

Research supporting the automatic use of information gathered through physical interactions with the environment can be found in many different areas of psychology. Such examples include the following:

- While standing on a balance board and making estimates of perceived objects (e.g., how tall is the Eiffel Tower?), participants leaning to the left routinely gave lower estimates than those standing upright or leaning to the right (Eerland et al., 2011). By leaning to the left, concepts associated with 'left' were presumably activated, such as the lower end of a number line. By having low numbers activated, participants were primed to make lower estimates.

- People thinking of the future tend to lean forward, while those thinking of the past lean backwards (Miles et al, 2010). People conceptualize 'future' as being ahead of them, and 'past' as being behind them.
- The perception of a cup's handle has been found to prime related motor responses in unrelated tasks (Tucker & Ellis, 2001).
- Pianists have shown activation in motor regions of their brain while recognizing recordings of their own performances (Repp & Knoblich, 2004).
- Wheeler (2000) presented participants with words either visually or auditorily, and when asked to remember these words in an fMRI scanner, activation was observed in the visual and auditory cortices in each condition respectively, which lends support that context-dependent learning effects may be partially explained with a grounded cognition perspective (see Conway, 2002).

Collectively, the evidence presented above makes a strong argument that information gained through a history of physical interactions with the environment is fundamental to cognitive processing. However, thus far the evidence supports online cognition: mental operations designed for immediate action utilizing information gained through similar experiences

The findings summarized above illustrate how bodily information, accrued over one's lifetime, influences people's perception of and interaction with their current environment. However, one of the strong claims of grounded cognition is that the same underlying bodily processes are responsible for offline processing as well. Conceptual information, knowledge, and memories are fundamentally embodied. Research in the area of language processing more generally, and lexical or semantic decision making more specifically, provides further evidence that supports this claim. From a grounded cognition perspective, people understand written language if they have had some degree of bodily interaction with or reaction to a word's referent.

People's reliance on grounded information to comprehend sentences is well documented in the literature. To understand a sentence's meaning, people are thought to use words and grammar as cues to activate and combine the perceptual symbols to simulate the described referents (Zwaan & Madden, 2005). Evidence for this assertion is seen in patterns of data that are not explainable from a classical cognition theory of language comprehension. Rather, from an embodied cognition perspective, people represent a sentence's subject differently based on context (Stanfield & Zwaan, 2001; Zwaan et al., 2002). For example, when reading the sentences "the eagle is in the nest" or "the eagle is in the sky", classical accounts would suggest that the 'eagle' in both sentences is the same amodal code. However, people identify images of the sentences' subject more quickly if the image depicts the subject in a sentence-congruent orientation, suggesting that readers prime different representations of eagles in both instances. For instance, after reading "the eagle is in the nest", people identify a picture of an eagle sitting more quickly than they identify a picture of an eagle flying. This finding is congruent with an embodied explanation in that people would be simulating words' referents rather than activating amodal codes. Similarly, people represent the distance between two objects described in a sentence differently based on context (Morrow & Clark, 1988). Specifically, when asked to read "the mouse approached the fence" or "the tractor approached the fence", people were more likely to judge the distance between the two objects to be greater if the sentence depicted a tractor than if it did a mouse. From a grounded cognitive perspective, this finding can be interpreted as people simulating both referents, and activating knowledge of the size of the referents, their likely speed of locomotion, and the distances from which each referent has typically been viewed. These findings are not predicted by amodal cognitive theories in that each word should activate the same amodal code regardless of context.

Further evidence of grounded effects in sentence comprehension is provided by Kaschak and Glenberg (2000), who presented readers with sentences containing made-up verbs derived from nouns (e.g., crutched, paper clipped, etc.). Their findings suggested that people would accept a novel verb as sensible if the physical object that constituted the verb was large enough to interact with the other referents in the sentence. For example, "Dennis paper clipped the potato to Janice" would be viewed as nonsensical, whereas "Janice crutched the potato to Dennis" was considered to be legitimate. As the verb in both instances is made up, the sentences should be unintelligible if people are simply using words as cues to access stored information. Similarly, people reading sentences describing two tasks being done concurrently are more likely to find the sentences as sensible if the tasks can physically be carried out together, and insensible if they cannot (De Vega et al., 2004). For example, "Morgan chewed gum while painting a fence" is sensible, whereas "Cameron played the drums while painting a fence" was deemed insensible. Both sentences, grammatically, are sensible and understandable. However, if people are simulating the words' referents, then there would be a conflict in the effort to simulate painting a fence and playing drums concurrently. Finally, it was also found that altering one's current physical state can alter the speed of sentence processing (Glenberg et al., 2005). Readers were asked to hold a pen with their teeth without lip contact (engaging the same muscles as a smile would), or with their lips, without touching their teeth (engaging the same muscles as a frown would). All readers processed sentences more quickly when the sentence contained information that was congruent with their simulated mood (e.g., processing sentences that contained 'happy' information while they were holding a pen that engaged muscles involved in smiling).

Abstract metaphor comprehension is another example of where applying a grounded cognition perspective has aided in understanding language processing. Metaphors, by their nature, are concepts that are understood in terms of other concepts. Phrases such as “it went over my head” or “it is beneath me” suggest that abstract concepts are often understood in reference to one’s body. Lakoff and Johnson (1980, 1999) have proposed a framework wherein conceptual knowledge of abstract metaphors is understood through previous grounded experiences with one’s body and environment. The concept ‘up’, for example, is commonly used to convey many different concepts. For example, up can convey more (“prices are going *up*”), control (“she works *above* me”), goodness (“things are looking *up*”), or rationality (“she *raised* the level of discourse”). The concept of ‘idea’ is another example. Specifically, ideas are conceptualized as physical objects when they are discussed; ideas *get into* one’s head or are difficult to *get across* to other people; ideas need to be *captured*. By relating abstract concepts to grounded concepts, people engage in a simulation process that enables comprehension.

Wilson and Gibbs (2007) empirically examined embodiment effects in abstract metaphor comprehension. Their data supported two central hypotheses. First, people who process metaphorical language prime the physical actions implied by the metaphor. Second, engaging in behaviours prime people’s processing of behaviour-congruent metaphors. Participants who had performed or had imagined performing an action were faster at identifying a metaphor that implied that action. For example, participants who imagined squeezing an object were faster to recognize the metaphor “grasp the concept” than any metaphor containing a different action (e.g., “put two and two together”), or no action at all (e.g., “you are in over your head”). Even though the metaphors did not require one to actually imagine physical actions to understand their meaning, the physical event underlying the metaphor was still primed, and vice versa. This is further evidence that information obtained from bodily experiences is important in language comprehension.

It could be argued that the evidence presented above regarding abstract metaphor comprehension reflects an automatic mimicry process underpinning cognition. Rather than activating symbolic representations, people may be parroting certain stimuli to activate information obtained through bodily experiences. Halberstadt et al. (2009) demonstrated a top-down embodied effect that challenges this assertion. Participants in their study were shown facial expressions of emotion that were computerized midpoint morphs of happy and angry faces. These faces, as a result, did not look like authentic expression of emotion. Each computer-generated face was, however, labelled as being happy or angry. Participants were to learn which faces corresponded to which emotion, despite the faces' lack of correlation with the labelled emotion. The dependent variable was electromyography (EMG) measurements of facial muscles. The researchers tested whether participants would automatically mimic the computer faces. At test, when the participants had to look at a face and identify its assigned emotion without a label present, the EMG recordings showed that people were activating muscles responsible for smiling when seeing a "happy" face morph, and the muscles for angry expressions when seeing an "angry" face morph. Participants were not mimicking. Rather, when seeing a stimulus that they knew to be happy, they were simulating their previous bodily experiences with happiness. This is precisely in accordance with a perceptual symbol system account of grounded cognition.

The studies reported in Chapters 3 and 4 have examined the behavioural implications of grounded cognition on the influence of meaning, as measured by grounded semantic richness, in visual word processing. Pexman (2012) defined semantic richness, generally, as the varying amounts of information, along any given semantic dimension, that are elicited when processing visually presented words. The idea of semantic richness may be used fruitfully in better understanding the observed effects of various grounded semantic dimensions in visual word recognition, including the dimensions of sensory experience (e.g., Juhasz, et al., 2011), imageability (e.g., Bennet et al., 2011, Cortese & Fugett, 2004; Yap, et al., 2015), body-object interaction (BOI; e.g., Siakaluk, et al., 2008a; Siakaluk, et al., 2008b), concreteness (e.g., Kanske & Kotz, 2007), and emotion information (Newcombe et al., 2012; see also Muraki, et al., 2019). These observed effects can thus be understood as arising because words that contain more grounded semantic richness due to many body-environment interactions are processed more quickly than words that contain less grounded semantic richness, due to fewer body-environment interactions. According to the PSS framework, facilitation of grounded semantic processing would be due to more efficient simulations of grounded semantic knowledge associated with greater levels of sensorimotor and emotional experiences with the environment contained in the semantically richer words. To continue the example given above, one may predict that, in visual word recognition tasks (such as semantic categorization tasks; SCT), the concept *dog* would be more easily processed and be responded to more quickly than the concept *purple*, because there are many more multimodal interactions a human can have with dogs (e.g., visual, tactile, olfactory, emotional) than with the colour purple (e.g., visual, but perhaps in special cases, emotional).

As noted, response latency advantages for words with greater levels of semantic richness have been reliably found in the literature (e.g., Strain, et al., 1995; Wellsby, et al., 2011). The influence of imageability effects have been found to be reliably facilitatory in lexical processing. For example, Cortese and Fugett (2004) had participants rate the imageability of 3,000 monosyllabic words. The participants provided the imageability ratings more quickly for words to which they assigned high imageability ratings than for words to which assigned lower imageability ratings (see also Binder, 2007; Li, et al., 2020; and Plaut et al., 1996 for other observations of facilitatory imageability effects). Juhasz et al. (2011) found that sensory experience ratings (the degree to which a sensory or perceptual experience is elicited by a presented word) account for a significant amount of variance in lexical decision task (LDT) response latencies. BOI has also been found to facilitate lexical processing (e.g., Siakaluk et al., 2008a; Tillotson, et al., 2008; Tousignant & Pexman, 2012; Van Havermaet & Wurm, 2014; Yap, et al., 2012). For example, Siakaluk et al. (2008b) observed shorter response latencies to words rated high in BOI in both visual (e.g., "Is this letter string a real word?") and phonological LDTs (e.g., "Does this sound like a real word?"). Yap and Seow (2014) found that words rated high in both positive and negative valence were responded to more quickly in a visual LDT. However, other research has found variability in the effects of valence ratings on semantic processing response latencies (e.g., Estes & Adelman, 2008; Kuperman et al., 2014; Vinson et al., 2014; Yap & Seow, 2014). Emotion information has alternatively been measured through emotional experience ratings (the degree to which a word evokes emotion information; EE). Higher levels of EE have been found to facilitate response latencies and accuracy rates of abstract noun categorization (Newcombe et al, 2012; see also Moffat, et al., 2015; Siakaluk, et al., 2014; Siakaluk, et al., 2016). Furthermore, the facilitatory influence of grounded semantic information has been observed outside of visual word recognition (e.g., tool identification: Witt, et al., 2010; mood-congruent sentence comprehension: Glenberg, et al., 2005). These findings suggest that grounded semantic richness is multimodal and includes multiple sensory (e.g., imageability, sensory experience), motor (e.g., BOI), and emotion (e.g., valence, EE) dimensions of grounded bodily experience with the environment.

In the visual word recognition studies summarized above, response patterns can be accounted for by the feedback activation framework of Hino and Lupker (1996). According to the feedback activation framework, visually recognizing words involves the activation of three types of units: orthographic, phonological, and semantic. Orthographic units process the spellings of words, phonological units process the sounds of words, and semantic units process the meanings of words. This framework further proposes that the activation of one set of units may influence the activation of the other sets of units through feedforward and feedback activation. The feedback activation framework may be used to interpret SCT response latency patterns. In a SCT, all stimuli are real words that vary along a particular semantic dimension (e.g., imageability, BOI, or EE), and a specific categorization decision is made (e.g., "Is the word concrete or not?"). According to the feedback activation framework, words with greater levels of semantic richness should activate more semantic units than words with lower levels of semantic richness, thereby allowing for faster settling of these units and thus facilitating categorization responses. Response latency differences are therefore hypothesized to be the result of varying levels of grounded semantic richness. For example, words referring to objects typically associated with increased physical interactions, as operationalized by higher BOI ratings, should activate a greater number of semantic units (i.e., the richness of one's sensorimotor simulation) related to such interactions, thereby facilitating responses to such words. In contrast, words referring to objects that are not typically associated with physical interactions should activate fewer semantic units, thereby leading to slower response latencies to such words.

One possible interpretation of the facilitatory effects described above is that increased levels of semantic richness should always automatically facilitate response latencies. However, results presented by Newcombe, et al. (2012) challenge this strict interpretation, such that facilitatory grounded semantic richness effects occur when higher levels of grounded semantic information are congruent with the decision criterion but are inhibitory when they are incongruent with the decision criterion. For example, in a SCT using the decision criterion, “Is this a concrete noun?”, faster response latencies and more accurate categorizations were made for concrete nouns rated higher in imageability and BOI than concrete nouns rated lower on both dimensions. These facilitatory effects are likely related to the idea that imageability and BOI ratings are diagnostic of concrete nouns, and hence congruent with the specific decision criterion used in that experiment. Importantly, however, concrete nouns rated high in EE were categorized less accurately as being concrete nouns than those words rated low in EE. This inhibitory effect is likely related to the idea that emotion information (as measured in this study using the EE dimension) is diagnostic of abstract nouns (Vigliocco, et al., 2009), and thus incongruent with the decision criterion. As such, the automatic activation of more emotion information for concrete words rated high in EE would signal that an abstract noun was being processed, thereby increasing the incongruency between what EE is diagnostic of (abstract concepts) and what the word actually is (a concrete noun). This incongruence leads to slower response latencies and/or increases the probability that participants make a wrong SCT response.

The inhibitory influence of task-incongruent semantic richness is difficult to reconcile with feedback models such as that proposed by Hino and Lupker (1996). In a feedback model of lexical processing, stimuli possessing more semantic richness should generate more feedback to other units, thus facilitating the resolution of contextual decision criteria. That is, it should be easier to recognize whether a stimulus satisfies a decision criterion if it has more semantic richness. This prediction is not supported by the data presented above. Barsalou’s PSS framework, however, can account for these data. Specifically, a visually presented stimulus will activate the perceptual symbol(s) that have been associated and experienced with the stimulus, and it is that symbolic representation that is compared against the decision criterion. Therefore, it can be hypothesized that there should be a gradient of congruence between automatically activated perceptual symbol(s) and the contextual decision criterion. However, grounded frameworks such as the PSS suggest that greater amounts of semantic richness should be reflected neurologically with a greater number of perceptual symbols' activation in perceptual, motor, and emotional cortices (see also Binder et al., 2016 for proposed primary features that comprise conceptual knowledge), with frontal brain regions recruited to integrate perceptual symbols into contextual task demands. The difference between these two frameworks can be dissociated by analyzing behavioural and neuroimaging data concurrently.

The findings presented above suggest that the effects of grounded semantic richness can be either facilitatory or inhibitory, depending on the congruency or incongruency between task demands and the grounded semantic dimension under examination. The specific semantic knowledge that is automatically activated may be considered as diagnostic information regarding a presented word's categorical membership in relation to current decision criteria. Importantly, this automatic activation of semantic information influences responding through being congruent or incongruent with top-down expectations imposed by task demands.

The finding that semantic information influences task performance in visual and phonological LDTs, where semantic information is not explicitly required to successfully identify a stimulus as a real word (orthographic information would suffice for visual LDTs and phonological information would suffice for phonological LDTs) further supports the conclusion that semantic knowledge is automatically activated when processing a word. According to the feedback activation framework (Hino & Lupker, 1996), the activation of semantic units provides feedback to orthographic units and to phonological units. However, whether the feedback from additional semantic unit activation is facilitatory or inhibitory depends on whether there is congruency between the nature of the semantic knowledge and the contextual task demands. For example, Yap et al. (2011) found that the number of senses associated with a visually presented word facilitated word recognition response latencies and accuracy in a LDT. Similarly, Siakaluk et al. (2008b) observed facilitatory effects for words rated high in BOI in a phonological LDT. As a result, it can be concluded that semantic information is automatically activated and subsequently influences lexical decision processing despite its contextual irrelevance. Conversely, inhibitory response latency effects have been observed in LDTs to words with synonyms or homophones (Hino et al., 2013; Pecher, 2001). The number of synonyms that a word has should be irrelevant in a LDT because orthographic information is the primary type of information that is used to successfully complete the task. In this instance, however, it is clear that one's knowledge about a word is being automatically accessed and that greater ambiguity in that word's processing is detrimental to response execution even when the processing was not contextually necessary.

To account for the effects described above, it is assumed that participants are automatically activating conceptual knowledge when presented with a word stimulus. The neurological nature of conceptual knowledge has been investigated, and is largely congruent with a grounded cognition framework. Importantly, conceptual knowledge has been found to be dynamic, flexible, and distributed across many brain areas including modality-specific regions (Fernandino et al., 2015; Hoenig et al., 2008; Kiefer & Pulvermuller, 2012). In an LDT, differential ERP patterns have been observed for action- and sound-related verbs (Popp et al., 2016). Experience is critical to conceptual representation. That is, repeated meaningful interactions with a concept leads to greater grounding of that concept's representation in motor and sensory brain regions (Kiefer & Trumpp, 2012). The specific conceptual features that are represented in sensory and motor brain regions are a function of an individuals' sensory and motor experiences during concept acquisition (Kiefer & Pulvermuller, 2012). Kiefer et al. (2007) trained participants with novel objects in different training conditions. In one condition, the shape of the object was diagnostic of its category membership, while in the other condition, a feature detail was diagnostic. During a categorization task of these novel objects, differential patterns of brain activity in sensory-motor brain regions was observed. These data suggest that conceptual knowledge is plastic and experience-dependent. It should be noted, however, that some researchers (e.g., Fernanidino et al., 2016a, 2016b) have used computer learning models to predict patterns of brain activity in heteromodal brain regions associated with sensory-motor experience (e.g., sound, colour, shape, manipulability, and visual motion). These findings would suggest that there are other processes involved in the realization of conceptual knowledge than reactivation of sensorimotor brain regions alone.

Abstract concepts have been observed to activate visual and action brain regions as early as 178 ms after stimulus presentation in ERP analyses of LDT experiments and 22 ms after stimulus presentation in conceptual decision tasks (Harpaintner et al., 2020a). The early effects of category-attribute interactions suggest that these effects reflect very rapid access of grounded conceptual information (Hoenig et al, 2008). When comparing fMRI patterns of activity between LDT processing and looking/pointing tasks, significant overlap was observed between looking and visual abstract words (temporal-occipital regions) and between pointing and motor abstract words (frontal and parietal motor areas) (Harpaintner et al., 2020b). Fernandino et al. (2021) found affective information represented in heteromodal cortices (e.g., frontal, parietal, and temporal cortex). These data were interpreted as reflecting experiential information insofar as lived experiences are multimodal in nature, and thus will recruit heteromodal brain regions to integrate the activity that experiences elicit in sensorimotor brain regions. Differential patterns of brain activity during the processing of the same emotion have been observed as a function of the context in which the emotion was being experienced (Wilson-Mendenhall et al., 2011).

With evidence steadily accumulating that grounded semantic richness influences responding in visual word recognition tasks, the discussion turns to the neurological implications of these findings. Specifically, if the propositions of grounded cognition are found to be theoretically useful, then there are two primary predictions that would stand out in contrast against purely amodal cognitive predictions. First, the regional brain correlates of conceptual knowledge processing should include sensory and motor regions. Some researchers, however, support the *grounded by interaction* hypothesis, which proposes that sensory and motor regions activate in conjunction with amodal knowledge centres to represent conceptual knowledge (e.g., Tomasino & Rumiati, 2013). For example, Ralph et al. (2017) propose the controlled semantic cognition framework that is a hub and spoke model of semantic processing. In this model, sensorimotor experiences are stored in modality-specific brain regions and comprise the spokes while a single transmodal hub is located in the bilateral anterior temporal lobes. Second, and more importantly, there should be measurably different patterns of neural activation as a function of the specific sensory and motor experiences that originally contributed to and thereby constitute the original experiences that led to the acquisition of that conceptual knowledge. For example, the neural activation of the concept of *coffee* could include visual centres for colour, tactile centres for temperature, olfactory centres for smell, and gustatory centres for taste, whereas the activation of the concept of *horizon* should only include visual centres.

To this end, research findings have supported these two grounded cognition hypotheses by observing activation in sensory and motor brain regions during cognitive tasks that do not explicitly rely upon grounded knowledge for their completion (e.g. Buccino, et al., 2001; Chao & Martin, 2000; Fadiga et al., 1997; Gallese et al., 1996; Hargreaves et al., 2012), and that the activated sensory and motor regions are a function of the original experiences (e.g., auditory regions for sound-related concepts: Kiefer, et al., 2008; motor regions for action-related sentences: Tettamanti et al., 2005; olfactory regions for smell-related words: González, et al., 2006).

Program of Research

To contribute to the growing literature that investigates the biological underpinnings of grounded conceptual knowledge, four experiments were conducted. These experiments serve to first, replicate and extend previous research in the field and second, to adapt non-invasive, novel, and comparatively accessible technologies to the field. In doing so, grounded cognition theories will be strengthened while simultaneously extending the methodological and statistical tools available to researchers investigating the patterns of brain activity evoked by the processing of grounded conceptual knowledge. To this end, the four experiments presented in the following chapters employed near-infrared spectroscopy (NIRS) and electroencephalography (EEG) to monitor the time course of brain activity elicited by an LDT and three SCTs, analysed with Bayesian credible intervals (Nathoo et al., 2018).

Near-Infrared Spectroscopy. In the experiments described in Chapter 3, near-infrared spectroscopy was used to investigate prefrontal cortex hemodynamic activity. NIRS technology is based on how near infrared light interacts with biological tissue (Bahnmueller, et al., 2014; Elwell & Hebden, 1999; Sato et al., 2013). Specifically, biological tissue is largely transparent to near infrared light from ~650-1000 nm yet is predictably absorbed by pigmented compounds such a hemoglobin (Amyot et al., 2012; Ferrari & Quaresima, 2012). By shining near infrared light into tissue, such as the cerebral cortex (through the scalp) and monitoring how much light emerges from the tissue after having been reflected and scattered by interactions with intervening tissues and fluids, (typically ~2-4 cm away from the light emitter), the hemodynamics (e.g., local blood volume) in tissue of interest can be measured. Critically, near infrared light is absorbed differentially by oxygenated and deoxygenated hemoglobin (O_2Hb and HHb respectively). By selecting the wavelength of emitted light and measuring how these wavelengths differentially escape the tissue(s) being measured, one can directly measure the relative concentrations of oxygenated hemoglobin ([O_2Hb]) and deoxygenated hemoglobin ([HHb]). Based on these values, blood volume and tissue metabolism (e.g., oxygen consumption) can be calculated.

NIRS overcomes many of the limitations of more popular functional magnetic resonance imaging (fMRI) techniques (Cui et al., 2011). For instance, one limitation when employing fMRI is that researchers must often oversample due to predictable difficulties in correcting for movement artifacts (Power et al., 2012; Yerys et al., 2009). NIRS measurements are taken using small detectors—called optodes—that are affixed to one's scalp and therefore move with one's head, thereby reducing movement artifacts and increasing the applicability of NIRS to grounded programs of research (Bahnmueller et al., 2014; Visani et al., 2015). A second limitation of fMRI is that measurements require placing participants in an enclosed and noisy environment that many people find claustrophobic and fear- or anxiety-inducing, or that is otherwise unsuitable for some participants (Doi et al., 2013; Furusho et al., 2002). As a result, NIRS is gaining popularity for investigating cerebral hemodynamics in children and adults who might otherwise find it difficult to participate in an fMRI study (Fishburn et al., 2014). These advantages collectively enable researchers to collect larger samples more easily (Doi et al., 2013).

Additionally, NIRS technology employs fibre optic cables to carry information between the measurement device and the optode, as opposed to electrical wiring, thereby enabling NIRS to be employed concurrently with technologies such as EEG (because there is no signal interference between the optical fibres and the EEG wires; Doi et al., 2013; Sawan et al., 2012; Zama et al., 2019). Recording NIRS signals concurrently with EEG has been validated as indexing the same neurological activity through neurovascular coupling; cortical regions that are more active produce more electrical activity and also consume more resources that need to be replenished with greater regional blood volume and oxygenation, despite the fact that both signals occur at significantly different speeds (milliseconds in EEG and seconds in NIRS; Balconi et al., 2015; Petzold & Murthy, 2011). Regional cerebral oxygenation increases following cognitive activity due to *regional perfusion overshoot*, wherein regional blood supply is replaced with fresh oxygen-rich blood following periods of activity that lead to depletion of resources, such as glucose or oxygen (Hermann et al., 2008; Rossi et al., 2012; Verner et al., 2013). Regional hyperoxygnation has been taken as evidence of functional activation (Hofmann et al., 2008), while the associated decrease in [HHb] has been interpreted as being due to faster wash out of deoxygenated hemoglobin due to the event-related increase of oxygenated hemoglobin (Rossi et al., 2011). Further, NIRS devices can sample at sufficiently high frequencies so as to be sensitive to neuronal activation in response to cognitive tasks (Bahnmueller et al., 2014), though the hemodynamic behaviours of interest often occur from 3-8 seconds after stimulus presentation (Moosmann et al., 2003). Finally, NIRS is dramatically more affordable, relatively portable (or at least more easily transportable), and has superior application potential for participants who have difficulty staying still (Arenth et al., 2007; Ye et al., 2009). Collectively, these attributes suggest that NIRS is a promising technology for investigating the neurological correlates of cognitive activity in a non-invasive manner.

Most NIRS devices are continuous wave (CW) devices (Kontos et al., 2014), which emit light continuously, varying between wavelengths that are absorbed differentially by O_2Hb and HHb. The measured data reflect relative changes in the concentrations of the two compounds. Alternatively, with additional mathematical processing, other devices provide additional information, such as the absolute values of total blood volume, the absolute concentrations of O_2Hb and HHb, and local tissue oxygen saturation (Calderon-Arnulphi et al., 2009). Devices that measure tissue oxygen saturation in addition to hemodynamic variables (i.e., hemoglobin concentration change) are called spatially resolved instruments, and those that measure absolute values are referred to as frequency domain devices (Strangman et al., 2002). These devices operate in a manner similar to a CW device, but during the emission of light at a particular wavelength, the light is modulated in intensity at approximately 100 MHz. This modulation produces a measurable emission intensity waveform that can be compared against the waveform of light that is detected at the scalp after it has passed through the tissue of interest. As it is known that photons slow down as they pass through tissue, there is a predictable phase shift in this waveform that can be detected by frequency domain devices (Elwell & Hebden, 1999). This phase shift information can be used to infer the actual distance that detected photons travelled before exiting the tissue, providing an index of penetration depth (i.e., how deeply the light penetrated into the tissue of interest before returning to the detector; this is roughly half the distance between the emitter and detector; Sato et al., 2013). This path length measurement can be used with a modified version of the Beer-Lambert law to calculate absolute values, as a function of the known absorption properties of O_2Hb and HHb (Elwell & Hebden, 1999).

It is important to note that the emitted light will pass through superficial tissue such as the scalp and skull. Such tissue is thought to be unresponsive to cognitive demands in most circumstances, and as such the absorption and scattering coefficients of this tissue can be viewed as constants in NIRS observations (though, it is possible for blood flow to the scalp to increase if the sensor begins to irritate the skin, or under particularly straining mental tasks).

The data obtained from NIRS experiments have been found to correlate strongly with the blood-oxygen level dependent (BOLD) signal from fMRI analyses, thereby validating the use of NIRS to detect cerebral hemodynamics as a measure of spatially sensitive brain activity occurring at most ~0.8 cm into the cerebral cortex; despite, like EEG, not being able to specifically detect subcortical activation (Amyot et al., 2012; Sato et al., 2013). Further evidence that NIRS is a reliable tool for cognitive research is found in experiments that explicitly examine its test-retest reliability by comparing participants’ recordings across multiple experimental sessions (6 months: Sato et al., 2006; one year: Schecklmann et al., 2008, Watanabe et al., 2003). It should be noted, however, that significant variability between participants has been noted in NIRS signals, thus making it vital that researchers record a substantial number of observations for statistical conclusions regarding cerebral hemodynamics (Amiri et al., 2014; Banville et al., 2017).

Some researchers have taken to reporting changes in [O_2Hb] as an index of cerebral activity, given its correlation with fMRI’s BOLD signal (Sato et al., 2013), though there is still some debate about whether [O_2Hb], total hemoglobin concentration ([THb]), or [HHb] is the best measure. Changes in [THb] would reflect the brain drawing on larger volumes of blood to meet increased task demands, whereas changes in [O_2Hb] would reflect a change the composition of regional blood, and a change in [HHb] would suggest the brain's increased use of oxygen during task demands. It has been concluded, however, that due to neurovascular coupling the increase in cerebral [THb] cannot be met with a proportional amount of oxygen consumption, and that this will lead to an increase in [THb] and [O_2Hb] and a resulting proportional decrease in [HHb] (Schroeter et al., 2002).

NIRS in Cognition. The application of NIRS to cognitive research is quickly growing in popularity and has been found to detect patterns of cerebral hemodynamics that are unique to specific tasks that a participant is completing (e.g., Banville et al., 2017; Herold et al., 2018; Pinti et al., 2020). These unique patterns demonstrate that the cerebral activity detected by NIRS reflects task-dependent cognitive processing rather than a generic state of activity associated with cognitive effort (Banville et al., 2017). To this end, non-invasive brain-computer interfaces have been developed that employ NIRS technology to recognize intentional brain activity, often with the goal of enabling individuals with disabilities to control devices such as wheelchairs (e.g., Banville et al., 2017; Khan et al., 2014; Morioka et al., 2014). Many researchers elect to monitor the prefrontal cortex (PFC) because it is the brain region behind the forehead, meaning that there is no hair on the skin to interfere with light emission or detection, the bone is thinner in this region than it is in other areas of the skull, and the brain-scalp distance is smaller in this region compared to others (Balconi et al., 2015). Nakadoi et al. (2012) demonstrated increased concentrations of oxygenated hemoglobin [O_2Hb] in the left PFC when participants evaluated the emotional significance of presented stimuli. In an *n*-back working memory task, participants are presented with a series of stimuli and are to respond when the current stimulus matches one that was presented *n*-back, where *n* is a number that varies from condition to condition. Fishburn, et al. (2014) observed increased [O_2Hb] in the PFC during an *n*-back task, though increases were observed bilaterally. This increase could be interpreted as a general component of greater cognitive effort given that a similar increase in [O_2Hb] was observed bilaterally in the PFC during random number generation and another *n*-back task (Hoshi et al., 2013). Increases in PFC [O_2Hb] and corresponding decreases in [HHb] have also been found during go/no-go animal detection tasks (Medvedev et al., 2011), and the Wisconsin Card Sorting Task (Fallgatter & Strik, 1998). Left dorsolateral PFC increases of [O_2Hb] have been observed during personal moral judgements, as compared to impersonal dilemmas (Dashtestani et al., 2018). Increases in [O_2Hb] and [THb] in the left PFC have been observed during confrontational naming tasks (making a forced choice of a label for an observed picture; Sakatani, et al. 1998). While actively reading aloud, participants have exhibited a decrease in [O_2Hb] and an increase in HHb (Fallgatter et al., 1998). The PFC has also shown increased [O_2Hb] and decreased [HHb] in verbal fluency tasks where a participant is given an alphabet constraint (e.g., 'words that begin with the letter R') and asked to generate as many exemplars as possible (Chaudhary, et al., 2011). During mental rotation tasks, decreases of [O_2Hb] and [THb] along with characteristic increases of [HHb] have been observed in the PFC (Banville et al., 2017). Collectively, these data suggest that NIRS is a reliable instrument for monitoring PFC activity and that it is sensitive to the demands of many types of cognitive tasks, including the PFC's role in mental manipulation and monitoring processes (Hoshi et al., 2003).

Examining brain regions other than the PFC is possible, though it can be more difficult given the presence of hair, and that the brain-scalp distance is often larger (Cui et al., 2011). For example, increased [O_2Hb] has been observed in the inferior frontal cortex (IFC) in language-impaired individuals compared to controls in a picture-pointing sentence comprehension task (i.e., which picture corresponds to a presented sentence; Fu et al., 2016). Increased [O_2Hb] has been observed in frontotemporal regions during an oddball paradigm (Tong et al., 2005). Additionally, in a Stroop paradigm, increases in [O_2Hb] and [THb] were observed in the left IFC on incongruent trials (Ehlis et al., 2005; Schroeter et al., 2002). Similar increases have been observed during a Stroop task in the superior parietal and frontal cortices of the left hemisphere (Hock et al., 1997). In a verbal fluency task, Hall et al. (2013) observed increased [O_2Hb] in the fronto-temporal areas corresponding to Broca's and Wernicke's areas. Banville et al. (2017) reported increased left temporal [O_2Hb] during word generation tasks, and bilateral temporal [O_2Hb] and [THb] increases during mental subtraction and motor imagery tasks. Increased [O_2Hb] has been observed in the occipital lobe when one is viewing pleasant stimuli and increased [HHb] when processing emotional stimuli (Herrmann et al., 2008). During voluntary motor planning, increased [O_2Hb] has been observed in premotor areas (Zama et al., 2015). Though more difficult to obtain, NIRS data from non-frontal brain regions have been obtained, and it is in line with other brain imagining studies.

A common convention in NIRS research is to employ a blocked experimental design, wherein a series of trials are presented rapidly, and mean amplitudes recorded. However, in light of pilot data collected for this program of research, it was deemed important to record more information than means alone, and thus a single-trial design was employed. In an event-related single trial design, there are more physiological metrics that can be recorded such as gain, dispersion, and lag (e.g., Schroeter et al., 2002).

In single-trial (event-related) go/no-go NIRS experiments, data is averaged across trial types and reported for the seconds following stimulus presentation. By doing so, experimenters can report the gain (peak amplitude), dispersion (duration of hemodynamic change), and the lag (time from stimulus presentation to peak hemodynamic amplitude) (Schroeter et al., 2002). These additional metrics stand to characterize the typical hemodynamic response more accurately to a variety of cognitive tasks. For example, Schroeter et al. (2002) conducted an event-related NIRS experiment using a colour-matching Stroop experiment. It was reported that [HHb] and [O_2Hb] gains and lag were greater for colour-incongruent trials. This difference in timing would have been missed had the researchers adopted a blocked design.

To validate a single-trial design for the current program of research, pilot data were collected that directly compared the data from a blocked design and a single-trial design with a 25 second inter-trial interval. The task for both experiments was a SCT with a decision criterion of "Is this word easily imageable?", with the go-trials varied on BOI ratings. BOI was chosen because it is one of the strongest facilitatory effects in SCTs (e.g., Siakaluk et al., 2008a; Sidhu et al., 2014). In the blocked design, stimuli were presented for 2500 ms or until a participant responded, and the intertrial interval was jittered between 1000 and 3000 ms to control for anticipatory effects. The data from this experiment were analyzed with a 2 x 2 analysis of variance (ANOVA: 2 hemisphere (left/right) x 2 condition (high/low BOI)). Disappointingly, no significant effects were observed; the effects of BOI on SCT performance were not evident in either PFC hemisphere's hemodynamics. In the single-trial design, however, stimuli were presented identically, though the intertrial interval was set at 25 seconds so as to be confident that cerebral hemodynamics had returned to baseline between trials (see Strangman et al., 2002; Tak et al., 2015). Rather than averaging the hemodynamic response over time and several trials, as in the blocked design, an event-related time course for each trial was obtained, and an average time course per participant per condition type was calculated. In this experiment, bilateral condition differences were evident, with high BOI trials showing no significant hemodynamic response, while low BOI trials showed a marked amplitude increase peaking approximately five seconds after stimulus presentation and returning to baseline approximately 10-12 seconds after stimulus presentation. In light of these data, the decision was made to adopt a 15 second inter-trial interval for the current program of research so as to give participants' hemodynamic response to each trial enough time to return to baseline between each trial.

In blocked go/no-go NIRS experiments, the mean hemodynamic amplitude for no-go trials would be obtained by averaging across a block of many sequential no-go trials, without any go trials. The reported mean hemodynamic amplitudes for go trials, however, would be reported as the average of a block of many sequential trials, the majority of which being go trials, yet containing some no-go trials. This is to say that the peak amplitudes reported for critical experimental trials in blocked designs includes data from some incongruent no-go trials as well. Furthermore, by taking an average across multiple trials completed within 20-30 seconds, mean amplitude is the only hemodynamic metric that can be meaningfully reported.

NIRS was thus chosen for the current research to examine this technology's application to the study of grounded cognition due to its high sampling rate and compatibility with EEG. By targeting the prefrontal cortex with NIRS measurements, the experiments presented in Chapter 3 will be able to address questions about the comparative effort to process semantically rich trials of varying task relevance for this cortical region.

Collectively, the findings summarized above serve to justify the application of NIRS technology in the current program of research. Explicit predictions for the NIRS data can be found in Chapter 3.

Electroencephalography. Many cognitive neuroimaging studies have taken to using technologies such as EEG to investigate the neural correlates of cognitive processing due to

EEG's strengths in monitoring time-related aspects of semantic processing. EEG was used in the experiments presented in Chapter 4. It is a non-invasive neuroimaging technique wherein electrodes are placed on the scalp to record electric polarity changes produced by spontaneous brain activity (i.e., the summed electrical activity produced by many neurons firing at once). This technology is used because of its non-invasiveness, relative affordability, and its high rate of sampling (e.g., up to 1000 Hz). EEG recordings have been found to be consistent within an individual over time, suggesting that people's characteristic brain wave patterns are reliable indices of cerebral activity (Tomarken, et al., 1992). By reporting EEG data as a relative change across conditions for each participant rather than absolute mean values, both ERPs and brain wave pattern changes can be compared across individuals (Antonenko et al., 2010). EEG does not accurately pinpoint specific brain regions that may be responsible for observed patterns of activation because EEG takes measurements from the scalp, when the source of the electric current is separated from an electrode by cerebrospinal fluid, the skull, and the scalp (Srinivasan, 1999). However, as the number of electrodes on the scalp is increased, the relative spatial accuracy improves. Though a region of activity can be deduced with some certainty, EEG cannot report whether the observed activity arose from local cortical tissue or from deeper structures (Andreassi, 2013). However, results have shown differential patterns of activation depending on the task that a participant is performing. For example, Khrizman (1973) showed that EEG can detect activity in the motor cortex and lower parietal lobe when participants are tapping their finger, yet activity is seen in the motor cortex and frontal lobe when performing a sorting task. Such observations support and validate EEG measurements in research.

EEG techniques rely on the accurate placement of electrodes (units ~6-8 mm in size, including a detecting wire and an electrolyte-soaked sponge) over known brain regions

(Andreassi, 2013). This is most commonly done by employing the 10-20 System (Jasper, 1958; Trans-Cranial Technologies Ltd, 2012). This system works by measuring the distance between predetermined physical landmarks on a person's head and placing electrodes in locations that are at 10% and 20% increments of those distances. The major landmarks used are the nasion (nose bridge), the inion (protuberance in the back of one's head over the occipital lobe), and the divot that can be felt immediately in front of one's ears. The skull's midpoint (top) is identified by marking the convergence point at 50% of the distance between the nasion and inion and also 50% of the distance between both ear landmarks. Then, using these landmarks and midpoint, electrodes are placed according to Jasper's (1958) validated distances. For EEG devices that employ more electrodes, there are guidelines put forth by the American EEG Society (1991) to guide electrode placement that ensure reliability between experiments. EEG software relies on a single electrode placed on a reference point (cheek, chin, shoulder) that will detect regular rhythmic patterns of activation in a participant's body to filter the EEG signal, thereby isolating the electrical activity that is unique to the brain (Andreassi, 2013). Many companies are beginning to market EEG caps that hold all electrodes in a fixed relative distance from one another, thereby adhering to the 10-20 System without need for single-electrode measurements (Trans-Cranial Technologies Ltd., 2013). This enables all electrodes to be placed in their correct positions simultaneously. By using such a cap, individuals' total time requirement for participation is reduced while also improving data quality and reliability across experiments and researchers.

EEG may also be used to detect ERPs, which are characteristic patterns of electrical activity that follow immediately after stimulus presentation that represent the immediate and automatic processes elicited by the stimuli by cortical neurons (Andreassi, 2013; Tomarken, et al., 2007). ERP data are often reported as distinct components in the ERP signal. Specifically, these components are typically labeled with a P or N, denoting whether the deflection is positive or negative compared to baseline (Luck, 2014). Further, each ERP deflection is given a numerical identifier using one of two typical naming conventions: either a single digit denoting the chronological ordering of the deflection (e.g., P2 would be the second positive deflection in a given ERP), or with a larger numerical identifier signifying the temporal epoch in which the deflection occurred (e.g., P200 would be a positive deflection that peaked between 200 and 300 ms after stimulus presentation, regardless of whether it was the first or second positive deflection) (Luck, 2014). The latter convention will be used here and in Chapter 4.

The deflections of interest for the experiments presented in Chapter 4 are the P200, N400, P600, and N600. The P200 has been interpreted as being reflective of and increased by automatic attention capture, task difficulty, and/or semantic richness (Kounios et al., 2009; Taylor & Khan, 2000). The variability of factors that influence the P200 suggests that this deflection broadly captures early automatic processing. The N400 is one of the most characteristic deflections in ERPs produced by semantic processing. Increased N400 amplitude has been typically associated with the processing of semantic or contextual irregularities such as when a sentence concludes unexpectedly (Heinze et al., 1998; Xue, et al., 2015). The P600 is a late deflection that may not contribute directly to response execution but has been interpreted as one’s automatic reanalysis of words that require additional processing (Coulson, et al., 1998; Gouvea, et al., 2010). By contrast, a negative deflection at the same time (the N600) is thought to be reflective of additional processing due to semantic incongruence, particularly in the processing of humour (Du et al., 2012).

Many ERP effects have been observed in semantic processing experiments. The amplitude of the N400 has been shown to decrease when processing words that occur frequently in written text (Assadollahi & Pulvermüller, 2001; Van Petten & Kutas, 1990), and increase for words with larger orthographic neighbourhoods (the number of words that differ from a word by one letter; Holcomb et al., 2002). Hauk & Pulvermüller (2004) demonstrated that the effects of word length and frequency on N400 amplitude are independent and additive. Concrete words (e.g., chair, dog) elicit a stronger N400 than do abstract words when other lexical variables are controlled (Barber et al., 2013). This concreteness effect is further enhanced when the concrete words have fewer associates (i.e., they have less semantic richness; Kounios et al., 2009). N400 amplitude is greater for nouns than verbs in a primed LDT (Rösler et al., 2001). When making a congruency decision, the N400 is lower for congruent words than to incongruent words (Neville, et al., 1986). In a sentence verification task, a pronounced N400 was observed when people were presented with the final sentence term in mismatch trials (i.e., reply "yes" to '[x] is not a [y]' or "no" to '[x] is a [y]') than to congruent trials (Fischler et al., 1983). Taken together, the data reliably show an N400 waveform deflection when semantic information is processed, and that the N400 is affected by the amount of semantic information required to successfully complete task demands.

Some ERP research has been done specifically on semantic richness and semantic categorization. In an SCT where word pairs were presented, and participants were to identify whether the second word was an exemplar of the first, N400 attenuation was observed for typical exemplars, "yes" responses, and when the word pairs were semantically related, regardless of category membership (Heinze et al., 1998). This demonstrates that the amount of processing necessary for an SCT is reflected in N400 amplitude. The N400 has been directly tied to embodied semantic processing and language comprehension (Willems et al., 2008). Xue et al. (2015) conducted an ERP study on the role of BOI in sentence processing in non-native speakers. ERPs were taken when participants read the last word in a visually presented sentence acceptability task. The target words were either high or low in BOI and could have been presented after a semantically rich or semantically poor sentence. A P200 was observed in central parietal regions (electrode P4) for all high BOI words. The N400 was most pronounced when high BOI words were presented in poor contexts versus rich contexts and was larger across all high BOI trials than in low BOI trials. When embodied information (a form of grounded semantic richness) is task-relevant, the N400 is attenuated. However, when a word activates an unexpected amount of type of information, the N400 is exaggerated, suggesting a higher amount of semantic processing is required to resolve task demands. Collectively, the data reviewed suggests that the N400 is the ERP deflection more frequently associated with semantic processing, and that congruence with task demands predicts its amplitude.

Although deflections occurring after the N400 may not directly reflect the processing of a word stimulus's semantic content (typically completed within the first 500 ms), they may reflect additional elaborative processing from anomalous stimuli (Kurchinke & Mueller, 2019; Wang et al., 2019). That is to say that the semantic content of a word stimulus may capture a degree of automatic attention that elicits additional processing due to its perceived irregularities. The P600 is a positive deflection that typically peaks approximately 600 ms after stimulus presentation and has been observed to be particularly sensitive to a stimulus's emotional content (Coulson et al., 1998; Gouvea et al., 2010). The N600 is another late component that has been interpreted as reflecting additional processing elicited by a stimulus's contextual semantic incongruence and humour (Du et al, 2012). It is possible that, by 600 ms after stimulus presentation, a word will have already been categorized in the context of current task demands. As such, ERP condition differences in the P600 and N600 can be interpreted as automatically elicited additional processing of stimuli that are perceived as atypical category exemplars (e.g., a concrete noun that evokes high levels of emotion information, which is typically associated with abstract nouns). ERP analyses in Chapter 4 extend to 800 ms after stimulus presentation so as to capture these indices of semantic processing. Full ERP predictions can be found in Chapter 4.

Experimental Tasks

In the LDT participants were presented with letter strings that were either real words or non-words and were to respond only to the real words. Real words varied in printed word frequency. The other three experiments were SCTs with real words as stimuli. In one SCT, participants were asked to respond only to words that were easily imageable, with all high imageability go trials varied in BOI ratings, with half of the words rated significantly higher in BOI than the other half. The other two SCTs used the same real word stimuli, with half the stimuli being abstract nouns, and the other half being concrete nouns. In one experiment participants were asked to respond to abstract nouns, and in the other experiment participants were asked to respond to concrete nouns. Both abstract and concrete nouns were manipulated for EE ratings with half of each word type being high in EE, and the other half significantly lower.

In all four experiments, participants were presented with a letter string, and were asked (1) to make a response if that letter string met a decision criterion for that experiment or (2) to make no response if the word did not meet the decision criterion. This procedure was selected because participant responses to target trials have been found to be shorter, less variable, and more accurate than when a two-choice procedure is employed (Gomez et al., 2007; Gordon & Caramazza, 1982). The response time differences between the two procedures have been interpreted as an additional process being required by participants to choose between two responses in addition to the cognitive process(es) associated with the experimental task. It has been found that participant discriminability (*d'*) and decision biases (log β) are comparable between the two procedures despite the shorter response times in go/no-go designs (Chiarello et al., 1988; Measso & Zaidel, 1990). In a two-choice design, participants who have been instructed to make a speeded response will feel pressured to respond to all stimuli, thus increasing the probability of making a *no* response if a stimulus is less familiar or less characteristic of the decision criterion. However, in a go/no-go procedure, if a stimulus does not quickly provoke a *go* response, processing will continue because participants do not have the option to make a *no* response, and this may result in a longer response latency that reflects the additional processing of less typical category members.

Experimental Procedure

While detailed explanations of the experimental methods are presented in Chapters 3 and 4, the commonalities are presented briefly here. For any single trial, participants were seated in front of a computer, instructed to attend to a fixation point (+). Following the inter-trial interval, a letter string was presented in capital letters, centred on the screen. If that letter string was congruent with that experiment's decision criterion (e.g., "Is this a concrete word?"), participants were to press the spacebar. If the letter string did not satisfy the current decision criterion, they were to do nothing. Go/no-go designs, as compared to more standard forced two-choice designs, are thought to be less cognitively demanding during non-lexical processing, resulting in fewer false positives, shorter response latencies, and higher accuracy on average (Lee, 2019). On average, the experiments lasted for 60-80 minutes. An inter-trial-interval of 15 seconds was used in all four experiments so as to allow hemodynamic activity to return to baseline following stimulus presentation.

Full behavioural predictions for the influence of these variables on participant response latencies are detailed in Chapter 3.

Independent Variables

The grounded semantic richness dimensions that were manipulated were BOI and EE. BOI was chosen because it has reliably been shown to facilitate response latencies to the presentation of easily imageable words in SCTs and, consequently, is thought to be diagnostic of how concrete concepts are represented (e.g., Hargreaves et al., 2012). Concrete objects are, by their nature, physical entities that allow for varying degrees of bodily interactions. For example, *spoon* refers to a concrete class of objects that are easily imageable and can be easily physically interacted with (and thus would have a high BOI rating), whereas *cloud* refers to a less concrete class of objects that are also easily imageable but cannot be easily physically interacted with (and thus would have a low BOI rating). EE was chosen because it is thought to be diagnostic of how abstract words are represented (Newcombe et al., 2012; Vigliocco, et al., 2009). Importantly, EE captures a dimension of emotion knowledge that represents information that is gained through one's emotion experiences across a variety of environmental contexts (Newcombe et al., 2012). As such, it was decided to operationalize emotion information as EE ratings. Abstract concepts are, by their nature, intangible concepts that refer to ideas rather than concrete objects that can be physically interacted with. For example, *envy* is an abstract concept with no physical referent. However, when experiencing or thinking about *envy*, one will have emotional associations with the experience of being envious. Full behavioural predictions for the influence of these variables on participant response latencies are detailed in Chapter 3.

By manipulating these dimensions of grounded semantic richness, target trials vary on comparative difficulty within an experiment such that some trials will be more easily recognized as satisfying the decision criterion. By analyzing easy and hard trials within an experiment, a greater degree of experimental control is possible than if the data were analyzed between different dimensions of grounded semantic richness. For example, in any given experiment, the decision criteria for a go-response is the same for all trials. This means that every single trial will involve the automatic activation of a word stimulus being integrated into the same contextual demands. As all other variables are controlled between trials, the behavioural, EEG, and NIRS differences between trials will reflect differential amounts of processing elicited by varying degrees of the same dimension of grounded semantic richness. Therefore, to the extent that a manipulated dimension is diagnostic of experimental decision criteria, the data that are produced will reflect the varying levels of a single dimension of grounded semantic richness and the executive efforts to apply that information to the current situation. Without such a difficulty manipulation, the patterns of activation between target trials would be predicted a priori to be qualitatively different according to the PSS framework, and thus increasingly challenging to interpret meaningfully.

Dependent Variables

The dependent variables were response latencies, response accuracy, full-scalp event-related potentials (ERPs) and prefrontal cortex (PFC) hemodynamics. The manipulated variables were word frequency in the LDT and grounded semantic richness in the SCTs. The specific dimensions of grounded semantic richness that were manipulated were BOI and EE. Specific details for the NIRS and EEG devices used in each experiment can be found in Chapters 3 and 4 respectively.

Summary

Several predictions are implicit in the philosophical perspective that conceptual knowledge is obtained primarily through one's sensory, motor, and emotion experiences with the environment. When processing any given concept, regardless of contextual demands, one may predict that the concept's sensory, motor, and emotion information is automatically activated. This automatic activation can then be hypothesized to influence experimental response latencies. Specifically, with greater amounts of sensory, motor, and/or emotion information associated with a given concept, that concept's processing may be able to reach a critical decision threshold more quickly than a comparable concept with fewer such associated information when that information is congruent with current task demands. However, if the fundamental nature of that concept's associated information is incongruent with current task demands, one can predict a response latency deficit when responding under such circumstances. These observations have been largely confirmed in the research summarized above. The current program of research stands to strengthen these behavioural observations through replication and extension. Additionally, by using a 15-second inter-trial interval, the data presented in Chapters 3 and 4 stand to demonstrate that these behavioural effects are not due to contextual priming/momentum created by responding to similar stimuli every few seconds and are actually fundamental to how conceptual information is processed.

By testing the neurological predictions of grounded cognition, the current program of research stands to contribute to the growing body of literature that endeavours to elucidate the nature of conceptual knowledge representation. While many ERP experiments analyze targeted electrode sites and report averaged or maximum amplitude within arbitrary boundaries, the current program of research provides a much more thorough contribution to the literature. From a grounded cognition perspective, many different brain regions are hypothesized to automatically contribute to the reactivation of conceptual knowledge. To investigate this dynamic process more fully, data were recorded and analyzed across the whole scalp. This difference allows for a more complete description of the cortical processing of conceptual knowledge. Furthermore, rather than average across time to report ERP metrics, the full ERP time course was computed at each electrode for each condition, and difference waves reported. This approach allows the current research to contribute a more thorough understanding of both when and where different dimensions of conceptual knowledge are processed. Moreover, a novel Bayesian analysis was employed so as to identify periods of meaningful condition differences confidently and accurately. This analytical technique stands to be a valuable contribution to future studies.

Finally, the current research is one of few to apply NIRS to the study of grounded cognition, particularly given the concurrent application of EEG. By monitoring PFC hemodynamic responses to single trial presentations, a novel and comparatively accessible neurological marker of cognitive processing is presented in Chapter 4. In a go/no-go experiment, such as those presented in Chapter 4, a participant must respond to a presented stimulus or inhibit the automatically generated response that is elicited. It is hypothesized that word stimuli that are poor category exemplars (e.g., imageable nouns that are rated low in BOI) will be more difficult to inhibit because their processing takes longer to reach a decision threshold. This additional processing may be reflected in the PFC due to the increased effort to identify such trials as category exemplars. To best capture and report these effects, a full time course Bayesian condition difference analysis was conducted as described above. As such, Chapter 4 stands to contribute to the field a novel technological index of grounded cognition processing as well as a novel analytical technique for reporting such data.

Together, the data presented in the following chapters examine, analyze, and describe the grounded nature of conceptual knowledge across four experiments, involving two neuroimaging techniques accompanied by behavioural analyses. Collectively, these data will contribute to the growing body of research that demonstrates the fundamentally grounded nature of human cognition.

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CHAPTER 3:

Using Functional Near Infrared Spectroscopy to Investigate Grounded Semantics

Surprisingly little conceptual knowledge research has been completed using functional near-infrared spectroscopy (fNIRS). This is surprising considering the close relationship between the data that NIRS provides, and the more familiar BOLD signal produced by fMRI. Being a comparatively affordable functional neuroimaging technique with applicable temporal and spatial resolution capable of monitoring cortical activity, fNIRS is well suited to cognitive research.

In lexical decision tasks (LDT), where participants are presented with a letter string and must decide whether the letter string is a real word or not, increases in oxygenated hemoglobin concentration ([O_2Hb]) have been observed during nonword trials in the left superior frontal gyrus and left inferior parietal gyrus alongside decreases in deoxygenated hemoglobin concentration ([HHb]) in the left inferior frontal gyrus (Hofmann et al., 2008). Similarly, during nonword trials, increased [O_2Hb] has been observed in the left frontal lobe in children (Sela et al., 2011), in older adults (Amiri et al., 2014), and in individuals with dyslexia (Sela, et al., 2014). Employing a go/no-go procedure in a LDT, Chen et al. (2010) recorded an increase in [O_2Hb] in the left temporal lobe for words with high phonographic neighbourhood ratings (words that have many similar sounding word neighbours when replacing a single phoneme with another in the same location). In an auditory lexical decision task, greater increases of [O_2Hb] have been recorded in fronto-temporal regions when participants are processing phonetically legal nonwords than for illegal nonwords, while greater increases were observed for all nonwords than for real words (Rossi et al., 2011).

In an auditory sentence verification variation of a semantic categorization task (SCT), where participants are typically presented with only real words and asked to decide whether the presented word matches a decision criterion (e.g., Is this a verb?), bilateral increases in [O_2Hb] in the inferior frontal gyrus were observed in response to syntactically anomalous sentences (Noguchi et al., 2002). When listening to spoken language, increased [THb] has been observed in the left temporal lobe when the heard language changes (Rossi et al., 2012). In another test of semantic processing, participants were presented with two words sequentially that comprised two-word phrases and were asked to read the words silently. Increased [O_2Hb] was observed in Broca's and Wernicke's areas on trials where the phrase was anomalous as compared to trials when the phrase was semantically correct (Horovitz & Gore, 2004). Similarly, increased [O_2Hb] has been observed in Broca's area during metaphor comprehension (Schneider et al., 2014). These few NIRS studies of semantic and conceptual knowledge processing demonstrate that the brain is hemodynamically responsive to semantic task demands.

Given the fact that NIRS is particularly suited to monitoring the prefrontal cortex (PFC) through the forehead, it has become increasingly applied to studying emotional stimuli as the PFC is among the brain regions implicated in emotional processing, experience, and regulation (Balconi et al., 2011; Balconi et al, 2015; Damasio, 1996). The orbitofrontal PFC has been implicated in the process of assigning emotional value and saliency to exogeneous stimuli (Doi et al., 2013). Activation of the PFC has been associated with activation of the autonomic nervous system when one is presented with emotional stimulation (Tanida et al., 2007). When processing emotional stimuli, increases in [O_2Hb] have been observed in the right PFC for negative or avoidance stimuli and in the left PFC for positive or approach stimuli, while bilateral [O_2Hb] PFC increases have been observed when participants are reinterpreting emotional stimuli

(Balconi et al., 2015; Herrmann et al., 2003; Kida & Shinohara, 2013a; Minagawa-Kawai et al., 2009). These PFC hemodynamic patterns to emotional stimuli have been interpreted as being either due to the emotional experience itself or with increased activity due to attending to and processing emotional stimuli (Hermann et al., 2003). When anticipating an incoming electric shock in a conditioning experiment, greater [O_2Hb] has been observed in the right PFC, supporting the observation that the right PFC processes stimuli with negative valence more than does the left PFC (Morinaga et al., 2007). Collectively, these data support the use of NIRS to investigate lexical cognition.

Prefrontal Cortex Functions

The PFC has been attributed with a broad range of flexible behaviour, the scope of which exceeds that of other animals (Miller & Cohen, 2001). In humans, the PFC is the most elaborated brain region, likely due to the increased sensory and cognitive processing abilities that humans possess (Miller & Cohen, 2001). The functional role attributed to the PFC has been described as exceeding the summed processes of its parts (Wilson et al., 2010). Although data suggest that the PFC is responsible for executive functioning (e.g., inhibition (Aron et al., 2003; Aron et al., 2004; Pardo et al., 1990), response preparation (Picton et al., 2006), cognitive flexibility (Miller & Cohen, 2001), and general intelligence (Duncan, 2001)), demonstrations of functional double dissociations are rare (Wilson et al., 2010). Experimental observations of PFC activity tend to be too task-specific to be interpreted as the actual function of the PFC, or so general (e.g., problem solving) as to lack theoretical usefulness (see Ramnani & Owen, 2004). As a result, it may be misleading to claim that any observed activation in the PFC reflects any one specific process. Rather, given the pattern of activation in the PFC across various experiments, PFC activity may reflect integrative processing of information generated and processed elsewhere in the brain

(Bechara et al., 2000). Given its key role in integrative functioning, the PFC is an ideal candidate for neuroimaging studies of cognitive processes such decision making in semantic categorization tasks.

Broadly speaking, lesions to the PFC frequently disrupt efficient organized behaviour, resulting in either a failure to initiate appropriate behaviour, or disinhibited and distracted behaviour (Duncan, 2001). PFC lesions often produce difficulty in following instructions when those instructions vary (Cohen et al., 1999). These disruptions suggest that the PFC ultimately controls human behaviour insofar as it decides when to initiate or withhold a particular behaviour (Picton et al., 2006). Increased bilateral activity has been observed during go/no-go experiments as compared to experiments that only require a go response, further supporting the interpretation that the PFC plays a role in organizing behaviour (Casey et al., 1997). It has been suggested that signals generated in the PFC serve to *bias* activity in other brain regions so as to efficiently meet current task demands (Miller & Cohen, 2001). An example of this is in the Stroop task when participants are presented with a coloured word stimulus that evokes automatic word and colour recognition activity – the PFC is thought to be responsible for biasing the colour recognition in favour of the stronger automatic semantic activation so as to facilitate task completion. Though it is possible that the PFC stores some information, the breadth of stimuli that have been observed to elicit activity in the PFC suggests that it may, instead, store algorithms so as to flexibly process information stored elsewhere (Duncan, 2001; Wood & Grafman, 2003). The PFC's responsibility for the flexible application of processing algorithms would imply that the PFC directs human behaviour by processing representations of stimuli, generated elsewhere in the brain, rather than by stimuli themselves (Goldman-Rakic, 1987). With a behavioural goal presented by one's current context, the PFC would then be responsible for integrating the product of more posterior brain regions so as to adapt to and achieve particular outcomes (Ramnani & Owen, 2004). Furthermore, it could be concluded that the PFC is therefore particularly involved in controlling attentional systems towards comparatively novel situations that do not already have an established behavioural template (Shallice & Burgess, 1998).

Despite the broad and flexible range of executive functions attributed to the PFC, some hemispheric differences have been observed, and some conclusions have been proposed regarding localized processing. For example, the left PFC has been associated with the processing of verbal information more so than the right PFC, though some activation in the right hemisphere is also evident (Duncan, 2001). The right hemisphere, however, has been associated with the processing of episodic memories when cognitive demands are low, though bilateral activation has been observed in high demand contexts (Nolde et al., 1998). In go/no-go experiments, individuals with lesions to the left PFC have frequently shown difficulty in preparing an appropriate response, while individuals with lesions to the right PFC have shown difficulty inhibiting responses (e.g., Garavan et al., 2006; Kawashima et al., 1996; Picton et al., 2006; Verfaellie & Heilmann, 1987). Similar behaviour has been observed in a stop-signal paradigm insofar as individuals with right PFC lesions had difficulty inhibiting their response, with the amount of difficulty positively correlated with the degree of impairment (Aron et al., 2003). This difficulty with inhibition in individuals with right PFC damage often results in a more generalized impulsive pattern of behaviour (Miller, 1992). It is possible, however, that the hemispheric differences that have been observed reflect interruptions to a more dynamic and integrative function of the PFC than would be concluded from such findings. For example, in macaques learning object-reward associations, regional lesions to the dorsal or ventral PFC of either hemisphere did not prevent the ability to learn the relationships, yet bilateral PFC lesions that included the premotor cortex did prevent the learning of object-reward relationships (Parker & Gaffan, 1998). This observation would suggest that the bilateral PFC is flexible in its processing of environmental information, with the ability to be recruited in multiple ways when solving a variety of problems (Wilson et al., 2010; also see Duncan's (2001) Adaptive Coding Model). Broadly speaking, then, the PFC can be described as playing a role in executive functioning, specifically in selective attention, filtering of perception, and biasing of behavioural responses in light of integrated information from more posterior brain regions (Bechara et al., 2000; Duncan, 2001; Koechlin et al., 2000; Wilson et al., 2010).

The PFC is frequently subdivided into smaller regions that have been investigated for localized function. The dorsolateral prefrontal cortex (DL-PFC) evolved from motor regions of the brain, has connections with the basal ganglia, and has a role in motor control (Wood & Grafman, 2003). As a result, this region is thought to play a role in the representation of action (Wood & Grafman, 2003). The DL-PFC has been observed to be active when an individual is processing exogeneous information (Christoff & Gabrieli, 2000). The dorsomedial PFC, by contrast, has been observed to activate during the processing of social information (Fletcher et al., 1995; Goel et al., 1995), and activity in this region has been interpreted to reflect the degree of relational complexity amongst environmental stimuli (Kroger et al., 2002). For example, to assess whether an encountered animal is dangerous, one must have awareness of one's efficacy, the distance to and size and species of the animal, as well as other factors including one's proximity to shelter or the presence of peers. The ventromedial prefrontal cortex (VM-PFC), with its connections to emotion and memory regions, has been implicated in the integration of bodily signals that are indicative of emotional experience with perceptual signals and memories (Doi et al., 2013; Wood & Grafman, 2003). The role of the VM-PFC has been described as processing incoming information about the environment and the emotion information previously categorized with familiar stimuli or to reactivate a learned emotion experience by signalling the appropriate neural structures (Bechara et al., 2000). Lesions to the VM-PFC prevent one from experiencing avoidance-related emotions such as that associated with taking a risk (e.g., the Wisconsin Card Sorting Task; Berman et al., 1995; Buchsbaum et al., 2005). In not experiencing risk-associated emotion states, individuals with VM-PFC lesions fail to learn to regulate their behaviour in accordance with real-world consequences (Bechara et al., 2000). Lesions to the ventrolateral PFC, by contrast, have been found to increase variability in one's responses, which has been interpreted as interference to one's ability to update and monitor incoming information (Picton et al., 2006).

Other localizations have been identified towards the rostral portions of the PFC. The orbitofrontal prefrontal cortex (OF-PFC) is located immediately above the eye sockets and is predominantly situated along the ventral surface, though some portion of it extends to directly behind the forehead. The OF-PFC has been implicated in the processing of social and emotional stimuli (Drevets, 2001; Koechlin et al., 2000), as well as in response inhibition (Siddiqui et al., 2008). Lesions to the OF-PFC result in individuals who act irresponsibly and generally lack affect (Hornak et al., 2003). In macaques in a go/no-go experiment with some rewarding stimuli, individuals with lesioned OF-PFC were more likely to respond to no-go trials, and their performance was worse still when the stimulus-reward pairings would change mid-experiment, suggesting the OF-PFC plays a role in learning and cognitive flexibility (Iversen & Mishkin, 1970). Activity in this region has been observed when individuals are touched with stimuli that produce pleasant or painful experiences more so than when touched by stimuli that produce neutral experiences (Rolls et al., 2003). Interestingly, this activity was not found with comparatively more intense pressure that produced neutral experiences, suggesting that activity in the OF-PFC is not reflective of stimulus intensity, but rather, of the valence of sensory experiences. The OF-PFC, as a result, has been interpreted as being involved in stimulus-reinforcement learning (Rolls, 2004). Within the OF-PFC itself, activity in the medial region has been observed when an individual is winning money, while activity in the lateral region has been observed when money is lost (O'Doherty et al., 2001). That activity is observed in the OF-PFC when money is used as a behavioural consequence highlights that the OF-PFC is responsive to *learned* relationships as primary reinforcers and punishments (Rolls, 2004). Collectively, these data suggest that the OF-PFC plays a role in assessing the emotional value of perceived stimuli as well as processing the representations of the relationships between stimuli and their behavioural consequences (Ramnani & Owen, 2004). As a result, the OF-PFC is one of the key regions implicated in the somatic marker hypothesis (Bechara et al., 2000). This hypothesis proposes that emotion experiences produce bodily states that affect cognition, and thus behaviour, through a 'body loop' (Poppa & Bechara, 2018). Evidence for this hypothesis comes from observations such as individuals with lesions to the OF-PFC failing to develop anticipatory anxious skin responses in risk-taking scenarios (Bechara et al., 2000). Thus, the OF-PFC would be implicated as a key region to investigate when one is perceiving stimuli with learned emotion information (Barret & Simons, 2015).

The frontopolar cortex (FPC) is the region of cortex directly behind one's forehead and is the most anterior brain region. Activity in the FPC has been reliably observed during the retrieval of episodic and recognition memory, suggesting its role in the processing of previously learned information (Duncan & Owen, 2000; Wagner et al., 1998). This region has also been found to activate during the processing of introspective states, further implicating the FPC as a brain region responsible for higher order cognitive processing (Christoff & Gabrieli, 2000; Ramnani & Owen, 2004). While the right FPC has been implicated in the retrieval of more familiar source memory (Tulving, 1983), the amount of activity in the left FPC has been shown to scale with the amount of perceptually detailed information within a particular memory retrieval (Ranganath et al., 2000). These activity patterns have been interpreted as evidence that the FPC is at least partly responsible for the binding of new information previously acquired knowledge, such as thinking about a known concept in a new context (Kroger et al., 2002). Experimental data has shown bilateral activation of the FPC during card sorting tasks (Berman et al., 1995), right hemisphere activation when responding a target stimulus feature (Rao et al., 1997), and left hemisphere activity during the comprehension of sentence semantics (Goel et al., 1997).

Despite the breadth of localized PFC functions, it has been observed that a wide variety of tasks recruit similar regions of the PFC, thereby suggesting that, as mentioned above, the function of the PFC is broad, and that its total capabilities exceed the sum of observed localizations (Duncan, 2001). Broadly speaking, the PFC is recruited when current task demands require top-down processing to guide behaviour in accordance with one's intentions, or perhaps to guide task-related behaviour when one's context requires learned behaviour that generates a less powerful neural signal than is automatically produced by a stimulus (Miller & Cohen, 2001; Ozawa et al., 2014). The PFC, then, can be thought to employ contextually relevant processes that are situationally adaptable so as to be reflective of previously learned associations (Wood & Grafman, 2003). With well learned associations being stored in posterior cortical regions, the PFC is recruited predominantly when one is performing a less familiar task or attending to less familiar relationship amongst stimuli (Koechlin et al., 2000). That is, activity in the PFC is likely not automatically elicited by a stimulus itself, but by the contextual relationships in which a stimulus is involved (Ramnani & Owen, 2004). As a result, the PFC is a region of interest for evidence of activity elicited by novel experimental tasks such as those in the experiments presented here.

Cognitive Investigations of the PFC using NIRS

To date, there has been no widely agreed upon method to investigate or analyze NIRS data in psychology (Bendall et al., 2016; Doi, 2013; Masataka et al., 2015). Various researchers employ different devices, each with a variable number of channels as well as different tasks, each with a variety of stimuli, and the data are neither processed nor analyzed consistently across experiments (Bonetti et al., 2018). As a result, a degree of subjective analysis is required to draw inferences from across NIRS studies. A recent review of NIRS experiments investigating PFC activity found that approximately 90% of such studies were research into verbal fluency or working memory, while the remaining 10% were loosely classified as “other” topics, sharing no particular theme or focus (Bonetti et al., 2018). This is particularly interesting given that NIRS has been noted as particularly well suited to the study of cognitive activity in the cortex, especially amongst populations and in contexts that are otherwise difficult for other neuroimaging technologies (Fishburn et al., 2014). A selection of the working memory and verbal fluency research will be reviewed below so as to provide context for the predictions made in the current program of research.

The most straightforward NIRS observation is that, during cognitive effort, cortical hemodynamic responses ([THC], [O_2Hb]) amplitudes scale linearly with task difficulty (Ayaz et al., 2012; Fishburn et al., 2014). Simply employing one’s working memory has been found to activate one’s PFC as evidenced by increased [O_2Hb] (Hetu et al., 2013). Moriya & Sakatani (2017) found that mental imagery, interpreted as the placing and maintenance of visual information into working memory storage, improves working memory performance and is associated with increased PFC [O_2Hb] during working memory tasks. It has also been observed that, as task demands increase in difficulty, neural activity becomes more anterior, independently of successful task completion, suggesting that this anterior activity reflects mental effort alone (Causse et al., 2017). An implication of this finding is that fNIRS is suitable for monitoring PFC activity during cognitive tasks as effort itself is observable. For example, in a n-back working memory experiment, PFC [O_2Hb] levels increase and [HHb] levels decrease as n increases while response latencies and accuracy worsen (Ang et al., 2014; Li et al., 2005). Furthermore, the time course of the hemodynamic response has been found to be sufficient in identifying the difficulty of a task that a participant is completing with an 84% accuracy for identifying hard blocks versus idle activity, 68% accuracy for identifying easy blocks versus idle activity, and 73% accuracy for identifying hard block from easy blocks (Ang et al., 2014). Similar data have been observed in mental arithmetic tasks in that the difficulty of the operation is correlated with the time course and amplitude of the PFC hemodynamic response (Ang et al, 2010; Tanida et al, 2004). McKendrick et al. (2014) found that working memory training increased [O_2Hb] levels in the left dorsolateral PFC and right ventrolateral PFC; and that bilateral [O_2Hb] levels in the ventrolateral PFC were negatively correlated with working memory performance. Of particular relevance to the research presented here is the observation that, in a verbal working memory task, the word frequency of a given stimulus was found to influence participants' behaviour (Berglund-Barraza et al., 2019). Specifically, participants were slower to respond yet more accurate in their responses, while the PFC hemodynamic response was lower when the target stimulus had low print frequency. These data were interpreted as indicating that low frequency words are unique compared to their high frequency counterparts, and were therefore easier to hold in working memory, thereby facilitating accuracy and requiring less effort from the PFC. So, for PFC NIRS data from working memory experiments, observed activity can be interpreted as the amount of effort required to execute a task-relevant response rather than the amount of processing elicited by a particular stimulus.

Within the verbal fluency experiments, it is generally found that simply engaging in the task of spontaneously producing words that meet a certain criterion (e.g., words that start with the letter "L") produces bilateral increases of [O2Hb] and decreases [HHb], with this effect more pronounced in the left hemisphere than the right (e.g., Kahlaoui et al., 2012). This effect has been found to be even more pronounced in individuals with panic disorder insofar as the amount of activity in the left inferior PFC is positively correlated with the severity of their panic disorder symptoms (Nishimura et al., 2009). Similarly, it has been found that individuals with depression, in addition to having less bilateral PFC activity in general, show less pronounced [O_2Hb] increases during verbal fluency tasks than do individuals without (Fu et al., 2018). Similar results were reported by Noda et al. (2012) who observed a negative correlation between right frontal and temporal [O_2Hb] levels during verbal fluency tasks and participants' severity of depressive symptoms. Collectively, these data suggest that NIRS is able to detect mental effort in the PFC as well as to discern between individual condition differences.

One area of PFC NIRS research that has received attention outside of working memory and verbal fluency is emotion experience and control. Although emotional experiences are thought to originate in subcortical limbic regions, it has been proposed that they are elaborated on, processed in the context of incoming information, and regulated contextually in more anterior brain regions, including the prefrontal cortex (Doi et al., 2013). As discussed above, there is a lack of consistency in NIRS research, and this issue extends to emotion research as well, with variability in the induction methods and behavioural tasks employed, with some researchers calling for greater rigor and highlighting a need for more replication due to inconsistencies in reported findings (Bendall et al, 2016). Regardless, the PFC is a region of interest for cognitive research into emotion experiences because emotion is thought to influence behaviour in both top-down and bottom-up manners (Bendall et al., 2016). That is, emotional experience will influence behaviour automatically due to altered brain activity that originates in more posterior limbic regions, as well as by causing an individual to employ cognitive strategies to regulate emotion experiences so as to complete contextual task demands. It is the latter effect that is likely to be captured by experiments monitoring PFC activity (Ozawa et al., 2014).

When presented with rewarding visual stimuli, [O_2Hb] levels in the orbitofrontal cortex have been found to increase (Rolls, 1996), and gentle pleasing touch has been found to increase [O_2Hb] levels in the bilateral anterior PFC (Kida & Shinohara, 2013a; 2013b). Emotion-laden music has been found to produce [O_2Hb] level changes in the PFC (Hermann et al., 2003; Tai & Chau, 2009, Yang et al., 2007) with NIRS signals uniquely characterizing the valence of the music with 70% accuracy (Moghimi et al., 2012a; 2012b), with negative valence and intensity ratings producing larger peak [O_2Hb] amplitudes. When presented with photos of their grandchildren, grandmothers have increased [O_2Hb] in the inferior and medial anterior PFC regardless of the child's expression, though this effect was more pronounced when the child was smiling (Kida et al., 2014). Minagawa-Kawai et al. (2009) observed similar patterns in mothers viewing photographs of their children. Increases in [O_2Hb] have been observed bilaterally when one is looking at negative images as compared to neutral images (Glotzbach et al., 2011). Hoshi et al. (2011), however, observed this effect for negative images to be predominantly lateralized in the right hemisphere, while also reporting bilateral [O_2Hb] decreases when participants were viewing positive images. Similarly, Ozawa et al. (2014) observed increased [O_2Hb] in the right anterior ventromedial PFC when participants were viewing negative stimuli. Herrmann et al. (2003) found that the degree of self-monitoring during a mood induction was positively correlated with the [O_2Hb] increase in the PFC, whereas this correlation was not found in mood inductions that were more self-reflective, suggesting that data obtained by NIRS from the PFC does not reflect an emotional experience itself, but rather the amount of additional cognitive activity associated with the experience.

In a depressed population, left dorsolateral PFC [O_2Hb] levels were found to be higher at rest in those individuals with comparatively greater frequencies of spontaneously occurring positive thoughts (Koseki et al., 2013). Tanida et al. (2007) have reported that sympathetic nervous system activity is positively correlated with right hemisphere PFC activity. However, it is important to consider whether the PFC activity is a component of one's emotional experiences or whether it reflects one's efforts to regulate one's emotional experiences. When recording from depressed individuals, it has been observed that the hemodynamic response in the right dorsolateral PFC is negatively correlated with the severity of individuals' anxiety symptoms, whereas bilateral antero-medial PFC activity is similarly negatively correlated with overall depressive symptom severity (Liu et al., 2014). These data were interpreted by the authors as the result of reduced cognitive control that ultimately results in depressive symptoms. Support for this interpretation comes from patterns of hemodynamic responses to distractions during the processing of emotional stimuli. Van Dillen et al. (2009) found that distractor tasks increased PFC hemodynamic response, while simultaneously reducing subjective reports of negative mood states induced by negatively valenced images. Similarly, Ozawa & Hiraki (2017) extended this finding by demonstrating that the speed of a participants' finger tapping (the distractor task) modulated the pattern of [O_2Hb] levels in the dorsolateral PFC, and negative emotion ratings with faster tapping leading to greater PFC activity and lower negative emotion ratings. These data support the interpretation that the intensity of the PFC hemodynamic response predominantly reflects cognitive control during emotion experiences.

In contrast to the data presented above, Hermann et al. (2003) did not observe any PFC hemodynamic differences to uniquely identify the processing of positive or negative stimuli. It has been suggested, however, that these differences in experimental results may stem from differences in approach to data analysis (Ozawa et al., 2014). More specifically, Ozawa et al. (2014) noted that, when positive and negative hemodynamic responses were compared to baseline data, the perception of both positive and negative stimuli could be interpreted as increasing PFC activity, whereas comparing the same hemodynamic responses to neutral stimuli, no statistically significant effects were observable. The variability amongst the findings presented above makes a coherent interpretation of NIRS technology's ability to detect the processing of emotional experience in the PFC rather difficult. Ozawa et al. (2014), however, found that task-irrelevant emotional images presented prior to task completion will modulate the hemodynamic response in the PFC elicited by an n-back working memory task, with greater hemodynamic responses following the perception of negative stimuli, suggesting that the effects of emotional control are evident in the PFC. In light of the working memory data presented above, it can be concluded that any stimulus that requires additional contextual processing will produce activity that is evident in the PFC with NIRS. Additionally, to the extent that the PFC is involved in the simulation of learned emotion associations, these effects may be detectable as well.

Although NIRS research has, to date, focused predominantly on verbal fluency and working memory, some research has been done in other domains of cognitive science. A central hypothesis to such research is that, as described above, brain regions that are more active have greater glucose metabolism, and that this consumption of resources will result in an observable increase in regional blood flow as homeostasis is restored (Bonetti et al, 2018). An extension of this neurovascular coupling is that, when participants' cognitive efforts increase, there should be more brain activity, and thus more pronounced hemodynamic changes that are detectable by fNIRS.

When presented with taste stimuli and tasked with committing the flavours to memory for later recognition, bilateral PFC [O_2Hb] increases have been observed, thus supporting the interpretation that PFC activity reflects contextual integration and cognitive effort (Okamoto et al., 2011). During the recognition phase of the taste memory experiment, PFC activity was predominantly lateralized to the right hemisphere. Children diagnosed with ADHD performing a Stroop task show less hemodynamic activity (typically right lateralized PFC) than do control participants (Inoue et al., 2012; Jourdan Moser et al., 2009; Negoro et al., 2010). When participants play video games for at least five minutes, lower levels of dorsolateral PFC [O_2Hb] are recorded (Matsuda & Hiraki, 2006). This observation likely reflects participants learning and adapting to the video game's demands and performing the five-minute block more easily. During the Wisconsin card sorting task and a verbal fluency task, bilateral increases of PFC [O_2Hb] were evident in 60% of participants (Sumitani et al., 2015). Although this effect was not evident in 10% of participants, lateralized increases were observed in the remaining 30%. However, there were individual differences in the hemispheric lateralization of this effect. These findings suggest that hemodynamic responses to task demands are highly individualized. However, it is also possible that individuals approach and complete the Wisconsin card sorting task in a variety of ways, thereby adding variability to the role that one's PFC plays in successful task completion.

In a go/no-go experiment, healthy control participants exhibit bilateral inferior PFC [O_2Hb] increases and [HHb] decreases during trial blocks with no-go trials as compared to blocks comprised exclusively of go trials (Herrmann et al., 2005). Similar observations have been made during stop-signal experiments when participants must inhibit an initiated response following a stop signal, with [O_2Hb] increases most pronounced in the right hemisphere (Boecker et al., 2007). Xiao et al. (2012) also observed inhibition-evoked right-hemisphere dominant [O_2Hb] increases during no-go trials in healthy control participants and found this effect to be lessened in participants diagnosed with ADHD or autism. The lessened hemodynamic response to inhibition efforts in ADHD and autism populations is correlated with these individuals' comparatively poorer task performances and is thought to reflect difficulty with inhibition processes. Nguyen et al. (2020; 2021) reported increased functional connectivity, as measured with fNIRS, in the right PFC as a function of successful go/no-go task completion such that participants with higher accuracy had greater functional connectivity in the PFC. Collectively, these data support the interpretations made above that NIRS technology can detect effort in the PFC, and that this activity will likely reflect cognitive effort with a right hemisphere lateralization if that effort is inhibitory in nature.

Experimental Predictions

Across the four experiments detailed below, lexical and semantic variables were manipulated in one lexical decision task (LDT) and three semantic categorization tasks (SCTs) to test predictions based in grounded cognition theory concerning the hemodynamic response in the anterior prefrontal cortex using fNIRS. Broadly speaking, it was predicted that some experimental conditions, having lower levels of lexical or semantic information, would be comparatively more difficult regardless of whether that information was explicitly necessary for successful task completion. fNIRS was employed to measure the hypothesized additional cognitive effort needed to respond to stimuli in these conditions as operationalized by greater [O_2Hb] and lower [HHb] in the anterior PFC. Additionally, it was predicted that these same trials would have slower response latencies and/or lower accuracy rates compared to those trials with stimuli rated higher in lexical and semantic information, as detailed below.

Experiment 1 was a go/no-go LDT with go trials having either high or low word frequency ratings. Behaviourally, it was predicted that words rated high in word frequency would be responded to more quickly and accurately than words rated low in word frequency. Word frequency was chosen as a lexical variable as a proof of concept to test whether cognitive effort could be detected with fNIRS in single-trial conditions. It was predicted that, because high frequency trials would be relatively easier trials for participants to recognize as real words, would produce the fastest response latencies, highest accuracy, lowest PFC [O_2Hb], and highest [HHb]. No-go trials, requiring no response, cannot have response latency predictions made about them in the current experimental design, though it is predicted that more errors will be made for low frequency words than for high frequency words. However, hemodynamically, it was predicted that no-go trials would require higher amounts of cognitive effort so as to inhibit participants' automatically generated response potential that is elicited by stimulus presentation, and that this inhibition would be reflected in greater PFC [O_2Hb] and lower [HHb] as a result, and furthermore that these changes would be evident predominantly in the right hemisphere. Two possible hemodynamic responses to the condition in which 'yes' responses were to be made to words rated low in word frequency were predicted. The first possibility was that the pattern of PFC hemodynamic response to low frequency go trials would look similar to responses to high frequency trials, but with more cognitive effort required, as reflected in greater amplitudes for [O_2Hb] and lower amplitudes for [HHb]. The alternative hypothesis was predicated on the assumption that stimulus presentation would automatically prime participants to respond and that this automatically primed response is fully inhibited in no-go trials for nonwords. Low-frequency words would be more difficult to recognize as a real word, and therefore inhibitory processes would remain engaged for longer than they would for high frequency words. This would explain the comparatively longer response latencies for low frequency words and would thus be predicted to produce a right-lateralized PFC response, similar to, but of lower intensity than, the fully inhibited no-go trials.

Experiment 2 was a SCT where go trials were either high or low in body-object interaction (BOI) ratings. This experiment aimed to replicate the behavioural observation that concrete nouns are responded to more quickly when rated high in BOI due to these nouns having greater levels of grounded semantic richness obtained through bodily interactions with the nouns' referents, thus allowing them to be processed more efficiently. Although the decision criterion for this SCT was "Is this an easily imageable word?", it was predicted that concrete nouns rated high in BOI would be processed more efficiently due to their higher levels of grounded semantic richness and thereby produce faster response latencies and higher levels of accuracy, despite BOI not being explicitly required for successful task completion. This cognitive efficiency was predicted to produce the comparatively lowest amounts of PFC [O_2Hb] and the comparatively highest amounts of PFC [HHb]. The pattern of hemodynamic response to no-go and low BOI word trials was predicted to be the same as for Experiment 1, with low BOI word trials being examined for their similarity to high BOI word trials or inhibited no-go trials.

Experiments 3 and 4 were also SCTs, but with half of the word stimuli being concrete nouns and half being abstract nouns. The decision criterion for Experiment 3 was “Is this an abstract noun?”, and in Experiment 4 was “Is this a concrete noun?”. Half of each word type was rated high in emotional experience (EE), and half low in EE. As detailed in Chapter 2, abstract nouns are thought to be grounded in one’s associated emotion experiences with the nouns’ referents. As a result, the behavioural and hemodynamic predictions for Experiment 3 are the same as for Experiments 1 and 2 with words rated high in EE being the easiest to process as abstract nouns, and thus producing the fastest response times, highest accuracy, and least pronounced hemodynamic responses. In Experiment 4, however, high EE concrete nouns are predicted to be the more difficult trials because concrete nouns are not thought to be as grounded in emotional experiences (see Chapter 2 for more discussion). As such, high EE concrete nouns in Experiment 4 are predicted to have the slowest response latencies, least accurate responses, and most pronounced hemodynamic responses. High EE trials will also be examined for their similarity to successfully inhibited no-go trials.

Method

Participants. In each of the four experiments, participants were University of Northern British Columbia students enrolled in psychology classes. 26 individuals participated in Experiment 1, and 25 individuals participated in Experiments 2-4. No participants were involved in more than one experiment. There were 20, 19, 18, and 19 female participants in Experiments 1-4 respectively. All participants asserted that they were native English speakers and had normal or corrected-to-normal vision. All participants received bonus course credit for their participation.

Apparatus.

Behavioural. For all four experiments, response latencies and accuracy were collected on a Dell Optiplex 7010 desktop computer running Superlab (version 5.0.3) software. Word stimuli were presented on a 21.5" Dell P2212H monitor in capitalized white Times New Roman 24-point font on a black background. Participants were positioned at a table and instructed to ensure that they could comfortably reach the spacebar of a keyboard for the duration of their experiment.

NIRS. NIRS data were acquired by OxiTS software (version 3.1.4.1) running on a Dell Optiplex 7010 desktop computer connected to a two-channel frequency domain device (OxiplexTS, ISS, Champaign, IL). Each channel consisted of a single optode with four pairs of emitters and a single detector, and with each emitter pair at a different distance from the detector. Within each emitter pair, one emitter broadcast near-infrared light at 684 nm and the other at 830nm. Each optode was placed above the brow ridge, below electrodes 1 and 2 (left and right hemisphere, respectively; see Figure 1, Chapter 4 for details), covering the anterior portion of the dorsolateral prefrontal cortex.

Lexical Decision Tasks. Experiment 1 consisted of an LDT with a go/no-go procedure, whereby the stimuli were letter strings (half being real words and the other half being nonwords) and participants were instructed to press the spacebar when the words were presented and to not press the spacebar when the nonwords were presented. Stimuli were the same as employed by Sears et al. (2008; Table 1). High frequency and low frequency words were selected such that there are no significant differences on orthographic neighbourhood, number of letters, number of morphemes, number of syllables, and phonological neighbourhood size. There were 66 high frequency words, 66 low frequency words, and 132 non-words, for a total of 264 trials in this experiment. An intertrial interval of 15,000 ms was used to allow prefrontal hemodynamics to return to baseline after each trial before a new letter string was presented.

Semantic Categorization Tasks. For Experiments 2, 3, and 4, participants completed a go/no-go SCT, wherein all the stimuli were words (half being exemplars of a particular decision criterion and the other half not being exemplars of that decision criterion; see below for the decision criteria used in these SCTs), and participants were instructed to press the spacebar when the exemplar words were presented and to not press the spacebar when the non-exemplar words were presented. For Experiment 2, the decision criterion was ‘easily imageable’; thus, participants were instructed to press the spacebar when easily imageable words were presented (e.g., *cage* and *prince*), and not to press the spacebar when less imageable words were presented (e.g., *dose* and *node*). For Experiment 3, the decision criterion was ‘abstract noun’; thus, participants were instructed to press the spacebar when abstract nouns were presented (e.g., *advance* and *discipline*), and not to press the spacebar when concrete nouns were presented (e.g., *basement* and *elbow*). For Experiment 4, the decision criterion was ‘concrete noun’; thus, participants were instructed to press the spacebar when concrete nouns were presented, and not to press the spacebar when abstract nouns were presented. As in Experiment 1, a 15,000 ms inter-trial interval was used in all three SCT experiments. As noted in Chapter 2, electroencephalography data were recorded concurrently, and those data are described in detail in Chapter 4.

As noted, Experiment 2 used the decision criterion of, “Is this word easily imageable”. The stimuli were the same as those used in Hargreaves et al. (2012), such that 36 words were rated high in BOI, 36 words were rated low in BOI, and these words were intermixed with 60 filler words that were rated low in imageability. Words rated high in BOI were matched with words rated low in BOI for word length, number of features, familiarity ratings, concreteness, imageability, print frequency, contextual diversity, orthographic neighbourhood size, and phonological neighbourhood size (Table 2).

For Experiments 3 and 4, the stimuli were the same as those used in Newcombe et al. (2012), such that the stimuli consisted of 70 concrete words and 70 abstract words. Half of each word type were rated high in EE, and the other half were rated low in EE. The high-EE words and low EE words were matched on HAL log frequency, age of acquisition, orthographic neighbourhood size, number of letters, number of syllables, number of morphemes, concreteness, and imageability (Table 3). As noted, for Experiment 3, participants were instructed to press the spacebar only to the abstract words, whereas for Experiment 4, participants were instructed to press the spacebar only to the concrete words.

Analyses.

Behavioural Data Processing. The behavioural data were processed in the following ways. First, participants were excluded from all analysis if their LDT or SCT accuracy rate was under 70%. Considering accuracy, no participants were removed from Experiments 1 and 4, one participant was removed from Experiment 2, and two participants were removed from Experiment 3. Next, words that were correctly responded to less frequently than 70% of the time were excluded from all analyses. No words were removed from Experiment 1. Eight words were removed from Experiment 2 (1 high BOI and 7 low BOI; 6.1% of the data), five words were removed from Experiment 3 (all were low EE; 3.5% of the data), and eight words were removed from Experiment 4 (7 high EE and 1 low EE; 5.7% of the data). Next, all trials with incorrect responses were removed from all analyses. One hundred forty-four responses were removed from Experiment 1 (2.1% of the data), 392 responses were removed from Experiment 2 (12.4% of the data), 364 responses were removed from Experiment 3 (11.3% of the data), and 332 responses were removed from Experiment 4 (10.2% of the data). Extreme response latencies were also removed from all analyses. Extreme response latencies were identified as faster than 250 ms and those slower than 2000 ms. No trials were removed for being faster than 250 ms in any experiment. Nine trials from Experiment 1 (<.01% of the data), 22 trials from Experiment 2 (<.01% of the data), 71 trials from Experiment 3 (.02% of the data), and 26 trials from Experiment 4 (<.01% of the data) were removed for being slower than 2000 ms. Finally, for each participant, response latency outliers were identified as those greater than 2.5 standard deviations from the cell mean of each condition and then removed from all analyses. Using this procedure, 69 trials from Experiment 1 (.01% of the data), 17 trials from Experiment 2 (<.01% of the data), nine trials from Experiment 3 (<.01% of the data), and 18 trials from Experiment 4 (<.01% of the data) were removed. From the remaining trials, average condition means (high- and low-frequency, high- and low-BOI, and high- and low-EE) were calculated for each participant and then averaged across participants. Separately, item-level analyses were conducted on the same remaining data by averaging response time latencies for each single word in each experiment. Averages were tested using Bayes Factors (ttestBF; R, version 3.5.3).

NIRS. To control for movement artifacts (that take the form of impossibly extreme values produced by an optode lifting from the skin), all Sat% scores greater than 100% were replaced with a value of 100% - a highly implausible value, but a possible one. All concentrations (μM) of THb, O_2Hb, and HHb greater than 200 μM were similarly replaced with the possible score of 200 μM. All NIRS data for the entire experiment were then filtered with a zero-phase, forwardreverse Butterworth filter with a low pass cut-off frequency of 0.5 Hz, high pass 1.5 Hz, ring and roll of 40 dB and 3 dB, respectively. Using each participant's entire data, standard deviations were then calculated for each condition in each hemisphere. Any participant whose data contained 30% or more data points that exceeded 2.5 standard deviations from the mean was excluded from the final NIRS analyses (2 participants were removed in Experiment 1, none from Experiments 2-4).

To control for drift within hemodynamic values across the entire experiment, the data was baseline corrected by subtracting the one-second average from each trials entire time course, thereby ensuring a stable baseline of comparison for each trial. Within-participant condition means were then calculated for each participant by taking the average of each 20 ms time point across all trials of each condition type for the 12 seconds following each stimulus presentation. These within-participant means were then averaged across participants, creating a single 12-second averaged global hemodynamic response for each hemisphere of each participant in each condition in each experiment. A 12-second difference wave was then calculated by subtracting the value of the Low Frequency/BOI/EE condition from the value of the High condition at each 20 ms timepoint.

As per Nathoo et al. (2018), within-participant Bayesian credible intervals were then calculated at each time point across the entire 12-second difference wave. This allows, with just a glance, an evaluation of the strength of the evidence across time, of a model that allows for the hemodynamic difference at each time point to be different than zero.

Results

Behavioural.

Statistical Analysis. Response latencies were analyzed in R (R Core Team, 2013) using the ttestBF function (Morey & Rouder, 2011). This function calculates a statistic (Bayes factor) reflecting the likelihood of the experimental data being produced by either a null hypothesis model wherein both conditions' data come from the same normal distribution (i.e., no treatment effect), or by a model reflecting a non-zero difference between conditions (i.e., a treatment effect). Although 'significance' is not a metric used in Bayes factor analyses, conventional benchmarks have been proposed: a Bayes factor of 3 is considered to be weak but statistically significant evidence, and a Bayes factor of 10 is considered strong evidence (Aczel, et al., 2017).

Experiment 1. The mean within-participant response latencies for low-frequency words and high-frequency words were respectively 814.33 ms (SE 32.92) and 786.40 ms (SE 28.88). For the item-level analysis, the mean response latencies for low-frequency words and high-frequency words were respectively 819.02 ms (SE 11.39) and 788.24 ms (SE 7.36).

The Bayes factor was 6.51 for the within-participant analysis, and 4.86 for the item-level analysis. These results should be considered statistically significant evidence that response latencies are better predicted by a model that includes word frequency than one that does not, and that high frequency words are responded to more quickly than are low frequency words.

There were 11 errors made in response to high frequency trials, 19 errors made in response to low frequency trials, and 111 errors made in response to no-go trials. Because of the low number of errors in Experiment 1, no analysis was conducted.

Experiment 2. In the within-participant analysis, the mean response latency for words rated low in BOI was 1045.66 ms (SE 38.21), and 932.37 ms (SE 36.27) for words rated high in BOI. In the item-level analysis, words rated low in BOI had a mean response latency of 1038.09

ms (SE 20.00), and a mean response latency of 934.40 ms (SE 11.55) for words rated high in BOI.

The within subject analysis produced a Bayes factor of 1,586,393 and the item-level analysis produced a Bayes factor of 937.31. Both analyses provide very convincing evidence that SCT response time latencies using the decision criterion of 'is the word easily imageable' are better predicted by a model that accounts for BOI than one that does not. More specifically, the results show that words rated high in BOI are responded to more quickly than are words rated low in BOI.

Accuracy data for the within-subjects analysis were analyzed with a two-tailed paired sample *t*-test. There were 32 errors made in response to high BOI trials, 150 made in response to low BOI trials, and 358 false alarms. The accuracies to high and low BOI trials were significantly different ($t(24) = 6.22$, $p < .01$). The item-level accuracy analysis was conducted with a two-tailed *t*-test with the number of correct responses to each high- and low-BOI word compared. The accuracies for high- and low-BOI words were significantly different ($t(34) = 3.94$, $p < .01$)

Experiment 3. In the within-subject analysis, the mean response latency was 1255.00 ms (SE 45.71) for abstract nouns rated low in EE and 1139.56 ms (SE 40.16) for abstract nouns rated high in EE. In the item-level analysis, abstract nouns rated low in EE had a mean response latency of 1227.56 (SE 17.75) and 1126.21 ms (SE 13.43) for abstract nouns rated high in EE.

The within-subjects analysis of response time difference produced a Bayes factor of 17,444.18, and the items-level analysis produced a Bayes factor of 949.76. Both analyses produce very convincing evidence that SCT response latencies to abstract nouns are better predicted by a model that accounts for EE than one that does not. More specifically, the data show that abstract nouns rated high in EE are responded to more quickly than abstract nouns rated low in EE.

Accuracy data for the within-subjects analysis were analyzed with a two-tailed paired sample *t*-test. There were 64 errors made in response to high EE trials, 185 made in response to low EE trials, and 224 made in response to no-go trials. The accuracies to high and low EE trials were significantly different ($t(24) = 8.22$, $p < .01$). The item-level accuracy analysis was conducted with a two-tailed *t*-test with the number of correct responses to each high- and low-EE word compared. The accuracies for high- and low-EE words were significantly different ($t(34) = 4.34$, $p < .01$)

Experiment 4. In the within-subject analysis, the mean response latency for concrete nouns rated low in EE was 977.72 ms (SE 21.36), and 1040.11 ms (SE 28.33) for concrete nouns rated high in EE. In the item-level analysis, concrete nouns rated low in EE had a mean response latency of 980.98 ms (SE 13.54), and 1040.55 ms (SE 25.83) for concrete nouns rated high in EE.

The within-subject analysis of response time difference produced a Bayes factor of 226, and the items-level analysis produced a Bayes factor of 4.16. The within-subjects analysis is convincing evidence that participants' SCT response latencies to concrete nouns are better predicted by a model that accounts for EE than one that does not, while the item-level analysis provides weaker (but still statistically significant) evidence that response latencies to concrete nouns can be better predicted by a model that accounts for EE than one that does not. More specifically, the data show that concrete nouns rated low in EE are responded to more quickly than concrete nouns rated high in EE.

Accuracy data for the within-subjects analysis were analyzed with a two-tailed paired sample *t*-test. There were 128 errors made in response to high EE trials, 31 in response to low EE trials, and 175 made in response to no-go trials. The accuracies to high and low EE trials were significantly different ($t(24) = -5.73$, $p < .01$). The item-level accuracy analysis was conducted with a two-tailed *t*-test with the number of correct responses to each high- and low-EE word compared. The accuracies for high- and low-EE words were significantly different ($t(34) = -3.68$, $p < .01$)

Near-Infrared Spectroscopy.

Experiment 1. NIRS data for the 12 seconds following stimulus presentation are presented for [O_2Hb], [HHb], [THb], and the regional tissue oxygen saturation (Sat%) in the left hemisphere in Figure 1, and for the right hemisphere in Figure 2. In the first four seconds after stimulus presentation, the immediate processing of presented stimuli is evident in the left hemisphere's characteristic decrease in [O_2Hb] and Sat% and increase in [Hb]. Left hemisphere [THb] decreases during the first 2 seconds and then slowly returns to baseline during the inter-trial interval. This pattern is nearly identical in the right hemisphere except for high frequency words, which do not show a meaningful pattern of decreasing or increasing. This interhemispheric difference suggests that letter strings are processed in the left hemisphere automatically, reflecting efforts to ascertain the linguistic properties of the stimulus. In the right hemisphere, however, the data reveal an inhibitory process in which no-go trials and low frequency words require more processing to inhibit response execution, while high frequency words are more easily recognized as real words, and therefore do not recruit the right hemisphere's inhibitory processes. Additionally, right hemispheric [THb] and [O_2Hb] decrease in the final four seconds of the intertrial interval, perhaps reflecting anticipatory inhibitory efforts as participants, having just inhibited responding, prepare to do so again.

Unfortunately, analysis of hemodynamic responses failed to reveal reliable condition differences. As described above, difference waves were calculated by subtracting the average hemodynamic response for one condition from another for the 12 seconds following stimulus presentation. These difference waves were then fit with Bayesian credible intervals. For a significant condition difference to be inferred, these credible intervals needed to not include zero. For example, in the left hemisphere, a model that includes effects of word frequency is statistically superior to a model of the null hypothesis that does not include effects of word frequency for approximately 100 ms beginning four seconds after stimulus presentation, with high frequency words having greater [THb] (Figure 3). Similarly, in the left hemisphere, the data show that at nine and nearly 12 seconds after stimulus presentation, for approximately 100 ms at a time, a model that includes effects of word frequency is statistically superior to a model of the null hypothesis that does not include effects of word frequency, with low-frequency word trials having greater [THb]. Given the brief duration, small magnitude, and erratic timing of these differences, these data are best interpreted as being the product of noise and not meaningful condition differences. As a result, no other hemodynamic condition differences will be reported here.

The data for Experiment 1 suggest that general patterns of lexical processing can be captured by fNIRS, but that these data lack statistical power to make conclusions about condition differences, if any exist.

Experiment 2. NIRS data for the 12 seconds following stimulus presentation are presented for [O_2Hb], [HHb], Sat%, and [THb] in the left hemisphere in Figure 4, and for the right hemisphere in Figure 5. As in Experiment 1, in the first 2-4 seconds after stimulation, evidence of stimulus processing is evident in the left hemisphere in the form of decreased [O_2Hb], Sat%, and [THb], accompanied by a slight increase in [HHb]. However, this pattern does not hold for words rated low in BOI. [O_2Hb] and [THb] increase shortly after stimulus presentation of words rated low in BOI, though these differences are small and likely attributable to noise, as discussed below. Sat% in the left hemisphere increases above baseline beginning 6 seconds after stimulus presentation for both no-go trials and for words rated low in BOI, while Sat% decreases for words rated High in BOI during the same timeframe. This difference could be indicative of additional semantic processing of High BOI words. In the right hemisphere, [O_2Hb] and Sat% increase above baseline approximately 4 seconds after stimulus presentation. [HHb] in the right hemisphere decreases during this time following the presentation of a no-go trial, unlike go trials where the levels stay near baseline. Collectively, these right hemisphere differences may reflect participants' efforts to inhibit their responses. However, [THb] in the right hemisphere during this time increases for both no-go trials and for words rated high in BOI, but not for words rated low in BOI. These differences challenge the interpretation of inhibitory effects in the right hemisphere from these data.

As with Experiment 1, analyses of the difference waves did not provide meaningful or reliable condition differences. For illustrative purposes, Figure 6 shows the difference wave between low-BOI and no-go trials of [O_2Hb] in the right hemisphere, including Bayesian credible intervals. Although there are several brief periods in this difference wave that suggest that a model that accounts for the effects of BOI is statistically superior to a model that does not, these periods align with bouts of particularly noisy data, and therefore are most likely best interpreted as false positives.

Experiment 3. NIRS data for the 12 seconds following stimulus presentation are presented for left hemisphere [O_2Hb], [HHb], Sat%, and [THb] in Figure 7, and for the right hemisphere in Figure 8. Bilateral [THb] increases are evident in participant responses to abstract nouns rated low in EE beginning approximately two seconds after stimulus presentation and persisting for the entire measured interval. The same pattern is observed bilaterally with increased [O_2Hb] in participant responses to words rated low in EE during the same period, though the effect does not begin until approximately four seconds after stimulus presentation in the left hemisphere. In the left hemisphere, [O_2Hb] increases in participant responses to words rated high in EE shortly after stimulus presentation but return to baseline during the intertrial interval. These data cannot be interpreted as increased effort to inhibit responses because increased concentrations were not observed during no-go trials. The increased [THb] and [O_2Hb] in the right hemisphere in participant responses to low EE trials may therefore reflect additional processing of atypical abstract noun exemplars.

Analyses of the difference waves did not reveal meaningful or reliable condition differences. For illustrative purposes, Figure 9 shows the difference wave comparing [THb] during high- and low-EE trials in the right hemisphere, with Bayesian credible intervals, where visual inspection of the data suggests sizeable differences. Although there are two brief periods in this difference wave that would statistically support the interpretations presented above, these periods align with spikes in the data, and therefore are most likely false positives.

Experiment 4. NIRS data for the 12 seconds following stimulus presentation are presented for [O_2Hb], [HHb], Sat%, and [THb] in the left hemisphere in Figure 10, and for the right hemisphere in Figure 11. No-go trials show increased [O_2Hb] and decreased [HHb] in the left hemisphere beginning shortly after stimulus presentation while [THb] increases for all three conditions. In the right hemisphere, [O_2Hb] increases for all three condition types, but does so more rapidly for no-go and low EE trials. [HHb] decreases are most evident for high EE trials starting four seconds after stimulus presentation and appears to increase for low EE trials approximately seven seconds after stimulus presentation.

As with the previous experiments, analysis of the difference waves did not reveal meaningful periods of hemodynamic differences. Figure 12 shows the difference wave of [O_2Hb] no-go trials subtracted from low EE trials as this effect looked to be significant in Figure 10. Although there is a marked period extending from approximately five to seven seconds after stimulus presentation where no-go trials appear to have significantly higher [O_2Hb] than do low-EE trials, comparison to Figure 2 shows that low-EE trials during this window are near baseline while high EE trials and no-go trials are above baseline. This finding is hard to reconcile with previous data as no-go trial hemodynamics, interpreted as inhibition processes, would be predicted to occur in the right hemisphere and should not require more effort in the left hemisphere than do no-go trials. As a result, given the conclusions of the previous three experiments, caution is urged in interpreting the data in Figure 12.

Discussion

The behavioural predictions of the four experiments detailed above were supported. In a LDT (Experiment 1), high frequency words were responded to more quickly. In Experiments 2 and 3, nouns rated high in grounded semantic richness (BOI and EE, respectively) were responded to more quickly and more accurately. These latter two findings were predicted because it is believed that greater levels of bodily and emotion experience with a word's referent leads to greater levels of grounded semantic richness in the conceptual representation of that word, thereby leading to more efficient processing and faster recognition of that word in the

SCTs used in these two experiments. In Experiment 4, concrete nouns rated high in EE were responded to more slowly and less accurately, thereby supporting the hypothesis that information obtained through emotion experiences are more indicative of abstract concepts and thereby increase the difficulty for participants to identify a concrete noun when EE ratings are high.

Behavioural Results.

The response latency data for all three SCTs support the hypotheses that one's sensorimotor and emotion experiences are integral to one's conceptual knowledge representation. Additionally, these experiences produced the predicted response latency differences. Experiment 1 replicated the well-established word frequency effect, with high frequency words being responded to more quickly and accurately than low frequency words. From a grounded cognition perspective, Experiments 2 and 3 examined the behavioural evidence that word stimuli containing more task-congruent grounded semantic richness (BOI and EE, respectively) would elicit faster response latencies. Experiment 4 tested the fundamental nature of emotion experiences in knowledge representation by recording response latency data when grounded semantic richness (EE) was incongruent with task demands.

Consistent with prior research, Experiments 2 and 3 demonstrated that participants responded more quickly to words rated high in grounded semantic richness (BOI and EE), whereas in Experiment 4, participants responded more quickly to words low in grounded semantic richness (e.g., congruency: Pexman, et al., 2003; Taler et al., 2013; incongruency: Newcombe et al., 2012). This differential influence of grounded semantic richness suggests that semantic richness obtained through bodily and emotional experiences with the environment is activated automatically when reading visually presented words. Newcombe et al. (2012) observed lower categorization accuracy rates for concrete nouns rated high in EE but did not observe a statistically significant response latency effect, as was the case in Experiment 4. The response latency and accuracy data of Experiment 4, taken together with Newcombe et al.'s (2012) observations, suggest that high levels of EE interfere with the recognition and processing of concrete nouns in SCTs. That is, high levels of EE are diagnostic of abstract concepts and, as a result, concrete nouns rated high in EE are more difficult to process as being concrete. These data support the hypothesis that conceptual knowledge is obtained through bodily and emotion sensations and behaviours, and that the activation of that knowledge automatically involves the reactivation of those very experiences regardless of whether doing so is contextually advantageous.

NIRS Results.

Although visual inspection of the NIRS waveforms for the 12 seconds following stimulus presentation suggested the presence of some event-related activity that supported the hemodynamic predictions made, a Bayesian analysis of difference waves did not reveal convincing evidence of condition differences. Although it is possible that these data suggest that the anterior PFC is not involved in lexical or semantic decisions, the literature review presented above makes this interpretation improbable. As a result, it is necessary to discuss possible reasons for why the results occurred across the four experiments presented above.

The first possibility regarding the lack of significant PFC activity detected by NIRS in these experiments is that, perhaps, the difficulty manipulation was not substantial enough to elicit measurably different hemodynamic responses in the anterior PFC on single trials. That is, despite the initial hypothesis that, for example, an abstract concept rated low in EE would be more difficult to identify as an abstract noun, and despite the many observations summarized above that PFC hemodynamics can reflect task difficulty, it is possible that, in the experiments presented here, manipulations of grounded semantic richness alone were insufficient to differentially activate the anterior PFC. This possibility could be investigated by using fMRI or a NIRS device with a greater number of channels. With a greater number of channels, it is possible that a more posterior effect would be evident because, as task difficulty increases, the associated brain activity becomes increasingly anterior (Causse et al., 2017). Thus, it is possible that the difficulty manipulation in these experiments was not reflected in the PFC. With fMRI, it is possible that the activity associated with condition differences in the experiments presented here would be detectable at a depth that NIRS cannot readily detect.

Another possibility is that the current experiments lacked statistical power to properly capture small cerebral hemodynamic changes. The majority of cognitive experiments employing NIRS technology use blocked designs. That is, even in go/no-go experiments, the data are collected over the course of several trials. For example, Inoue et al. (2012) employed a go/no-go design where "go trial" data were operationalized as the average hemodynamic amplitude across 2-minutes of go trials and "no go" data were operationalized as the average hemodynamic amplitude of 2-minutes of mixed trials, half of which were go trials and half of which were no-go trials. Inoue et al. (2012) used a 16-channel NIRS device covering a 14x3.5 cm area of the forehead, using wavelengths 730 and 850 nm, sampled at 3 Hz. Hemodynamic differences in experiments such as these would therefore reflect periods of time where response inhibition occurred, rather than reflect the inhibition process itself, as was attempted in the experiments reported here. Ang et al. (2014) reported 'single trial' classification of task difficulty using 32-channel NIRS technology using wavelengths 760 and 830 nm, sampled at 1.81 Hz. However, an assessment of their research design shows that a trial in this experiment lasted several minutes. It can be concluded, then, that most researchers measure cerebral hemodynamics over the course of several minutes of sustained cognitive effort so as to capture recordable effects in the brain. In conducting the literature review for the experiments presented here, no researcher explicitly stated this justification for their research design, though blocked designs certainly appear to be the norm. In designing the experiments presented here, the decision to employ a single-trial design with long intertrial intervals was driven by the fact that hemodynamic responses are slow to return to baseline and that the sampling rate of NIRS is sufficiently high as to fully capture the shape of the hemodynamic response (Pinti et al., 2018). Earlier pilot data related to this research suggested that single-trial PFC condition differences were obtainable in SCTs, with the hemodynamic response primarily located in the right hemisphere. Future replications of these experiments would do well to contrast the hemodynamic response from blocked and single-trial designs so as to investigate the full range of cerebral hemodynamics elicited by lexical and semantic decisions.

Another possible factor that may have contributed to the absence of clear hemodynamic data in these experiments is the equipment itself. More specifically, the OxiplexTS is a two-channel device with flexible optodes that allow it to be affixed to the scalp for cerebral monitoring. The optodes on the OxiplexTS are approximately two inches wide and three inches long, with fixed emitter-detector distances. The first implication of employing the OxiplexTS is that only a very limited region of the cortex can be monitored and, if the event-related hemodynamic activity is not occurring in precisely that location, it will be difficult to detect. The pilot data mentioned above suggested that the anterior PFC was a viable location for the observation of hemodynamic responses elicited by semantic categorization. However, those pilot data were collected with NIRS alone; EEG was not collected concurrently. As a result, it is possible that, in accommodating the EEG caps, the optodes were placed in a more anterior location than they were during pilot data collection so as to allow for accurate electrode placement. With a different NIRS device designed to accommodate EEG electrodes, or that allowed for customized emitter-detector placement, data collection would have been possible at more lateral locations. Using sizeable optodes with the ability to adjust emitter-detector distances is normally not a concern when monitoring cerebral activity. However, it does limit the positions that are available when simultaneously recording EEG data.

As detailed above, both the dorsolateral and ventrolateral PFC have been implicated in cognitive processes beyond integrative contextual processing, which would have expanded the breadth of conclusions that could be drawn from the experiments presented here. Additionally, it would have been ideal to be able to monitor multiple brain regions. A device with additional channels would have allowed for recording from frontotemporal cortex along with the anterior and lateral PFC. Doing so would have increased the number of possible PFC functions that could be inferred from the data and would increase both spatial acuity and statistical power. Finally, for Experiment 2 in particular, it would have been optimal to measure from the motor, somatosensory, and parietal cortexes given the grounded cognition hypothesis that conceptual knowledge involves reactivation of the neural regions involved in forming that conceptual knowledge. As such, NIRS should be able to detect activity in these cortexes during the processing of referents that one has bodily experience with (see Hargreaves et al., 2012 for fMRI data supporting this hypothesis). Unfortunately, pilot data associated with this research suggested that the OptiplexTS was unable to obtain interpretable data from this region. This is unsurprising given that the brain-scalp distance is comparatively greater here than at the PFC.

In Experiments 3 and 4, there are two possible reasons why grounded semantic richness effects were not observed in the PFC. The first is spatial in nature. Specifically, it is possible that the effect of emotion information in the simulation and processing of conceptual knowledge happens predominantly in the ventromedial PFC (e.g., Ozawa et al. 2019). Future extensions of this research would do well to record from as many locations as possible so as to test this hypothesis. The second reason concerns how grounded semantic richness attributable to emotion experiences was operationalized in these experiments. Specifically, as discussed in Chapter 2, emotion information was operationalized as EE ratings. That is, positive and negative valence were collapsed into a single dimension that captures the ease by which a concept elicits an emotion experience. Previous research has shown that EE accounts for response latency variability above and beyond that of positive and negative valence (e.g., Moffat, et al., 2015; Newcombe et al., 2012; Siakaluk, et al., 2014; Siakaluk, et al., 2016). However, as detailed above, hemispheric differences have been observed during the processing of positive and negative stimuli, with negative stimuli primarily activating the right PFC and positive stimuli primarily activating the left PFC (Balconi et al., 2015; Herrmann et al., 2003; Kida & Shinohara, 2013a; Minagawa-Kawai et al., 2009). As a result, it is possible that the PFC was involved in the automatic processing of emotion information during the abstract and concrete noun SCTs in Experiments 3 and 4, but due to positively and negatively valenced words being averaged together during data analysis in these experiments, the associated PFC hemodynamic activity may not have been captured here. That is, if the right hemisphere was active and the left hemisphere was inactive during the processing of negatively valenced words, and this pattern reversed for the processing of positively valenced words, then the act of averaging the signals across positive and negative word trials could produce an artificial null result. Unfortunately, testing this particular hypothesis will be difficult.

Future replications of Experiments 3 and 4 will have to be careful when trying to ascertain whether there are hemispheric differences when participants are processing concepts with high positive and negative valence. One approach to testing this would be to replicate the current design with word stimuli that were exclusively positively or negatively valanced. However, participants may quickly learn to respond to a word's valence rather than its abstractness or concreteness. To prevent this possibility, the abstract and concrete nouns would need to be balanced on their valence, and separate experiments may need to be done regarding positive and negative valence as a result. Though possible, this would be a challenging task. Another option would be to replicate the current design but with at least twice the number of trials to increase statistical power sufficiently so as to allow for the analysis of valence effects in addition to the effects of EE. A consequence of this design would be that the experiment would require nearly three hours to complete without greatly reducing the inter-trial interval which would have the unfortunate effect of obscuring the time course data for individual trials. These concerns would need to be taken into consideration prior to future investigations of the hemodynamic response to the processing of emotion information in the PFC during SCTs.

A final consideration is that the data were too noisy to detect real effects in these experiments. One reason for this could be due to the fact that NIRS signals were recorded concurrently with EEG data for an average of 80 minutes per session. Once participants were seated comfortably and an EEG cap fitted to their head, the optodes were placed through and under the EEG cap. To keep them in place, cohesive tape was wrapped around the participants' heads several times. However, in analyzing the EEG data for Chapter 4, it was clear that data integrity suffered over the duration of the experiments. That is, the electrodes lifted over the course of the experiments. Due to the constant pull of the elastic straps that comprise the EEG caps, upward pressure created by the participants' hair, or participant movement throughout the lengthy session lifting can occur, causing the EEG cap or cohesive tape to be repositioned. Regardless of the reason, evidence of data degradation over time in Chapter 4 highlights the possibility that the optodes may have changed position as well during these experiments, thereby adding variance to the NIRS signal. Future replications would do well to employ NIRS devices that are more appropriately designed to integrate with EEG or to maintain contact on the scalp for extended periods of time.

Conclusions.

Behaviourally, the data support the conclusion that grounded semantic information is an automatic component of conceptual processing, even when it is not conducive to successful task completion. It is interesting and important that the dimensions of grounded semantic richness manipulated in these experiments were not explicitly relevant to task completion because the results therefore support the ideas that, when categorizing nouns' concreteness or abstractness, a person need not (a) be explicitly aware of their bodily interactions with imageable objects nor (b) be aware of their emotional experiences with concepts.

The addition of NIRS monitoring during LDT and SCT performance was intended to capture differential prefrontal activity due to the increased effort required to process or inhibit specific trials as a function of their task congruency. These data stood to serve as an indirect physiological correlate of conceptual processing or of inhibitory effort. The NIRS data did not reveal meaningful condition differences in the PFC during task completion. Participant response latencies illustrated that grounded semantic dimensions of conceptual knowledge were activated automatically when completing an SCT trial. Unfortunately, however, these effects were not evident in the PFC data obtained via NIRS. Future studies would do well to continue this line of research while incorporating a greater number of optodes and measuring from multiple brain regions. By doing so, the clarity of the obtained data may be enhanced by being able to filter NIRS data using nearby optode locations as a covariate, and thereby increasing the power of NIRS to lead to observations of the semantic effects evident in the behavioural data reported here.

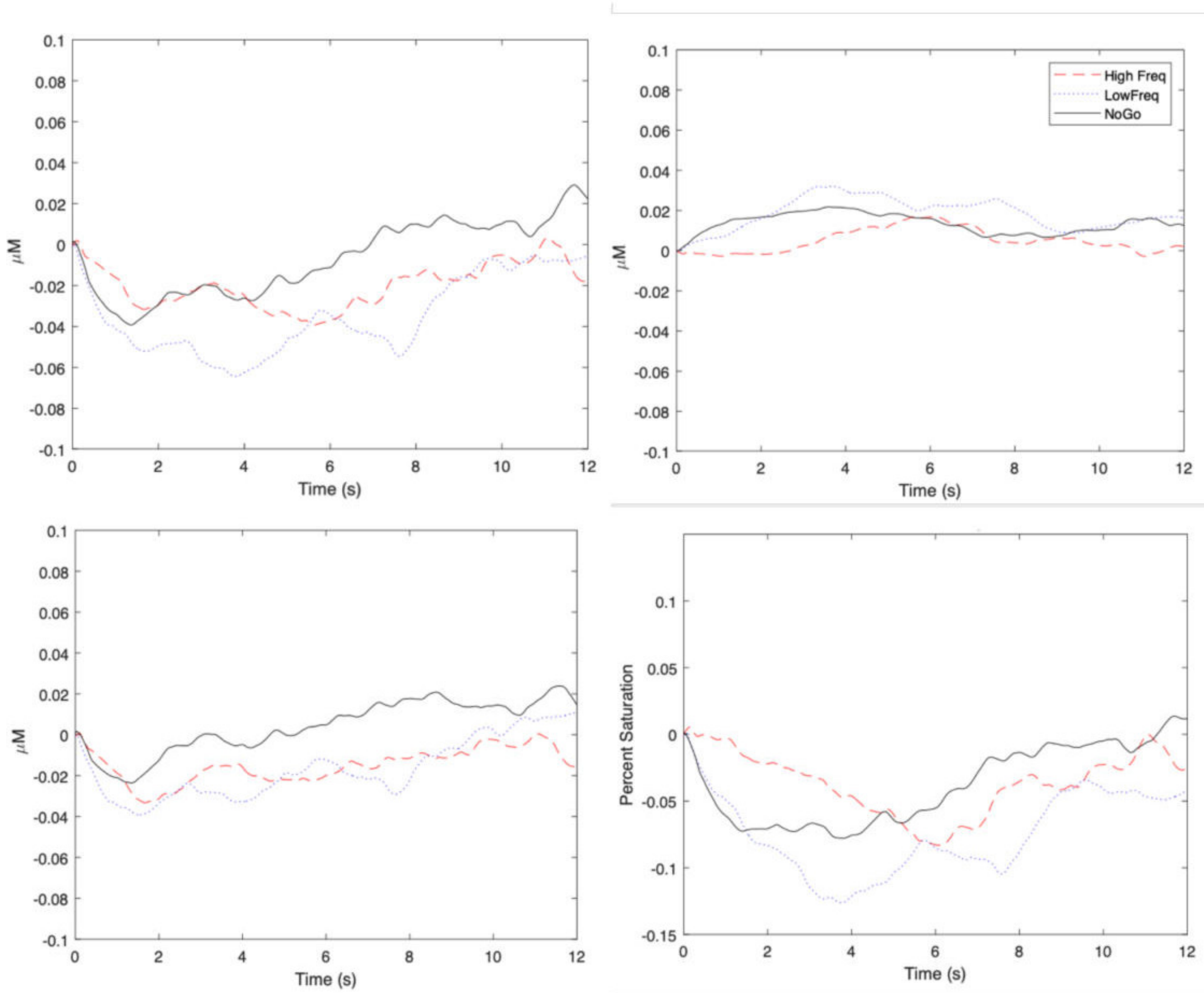

Figure 1. Clockwise, from top-left: NIRS time course data for left PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 1. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

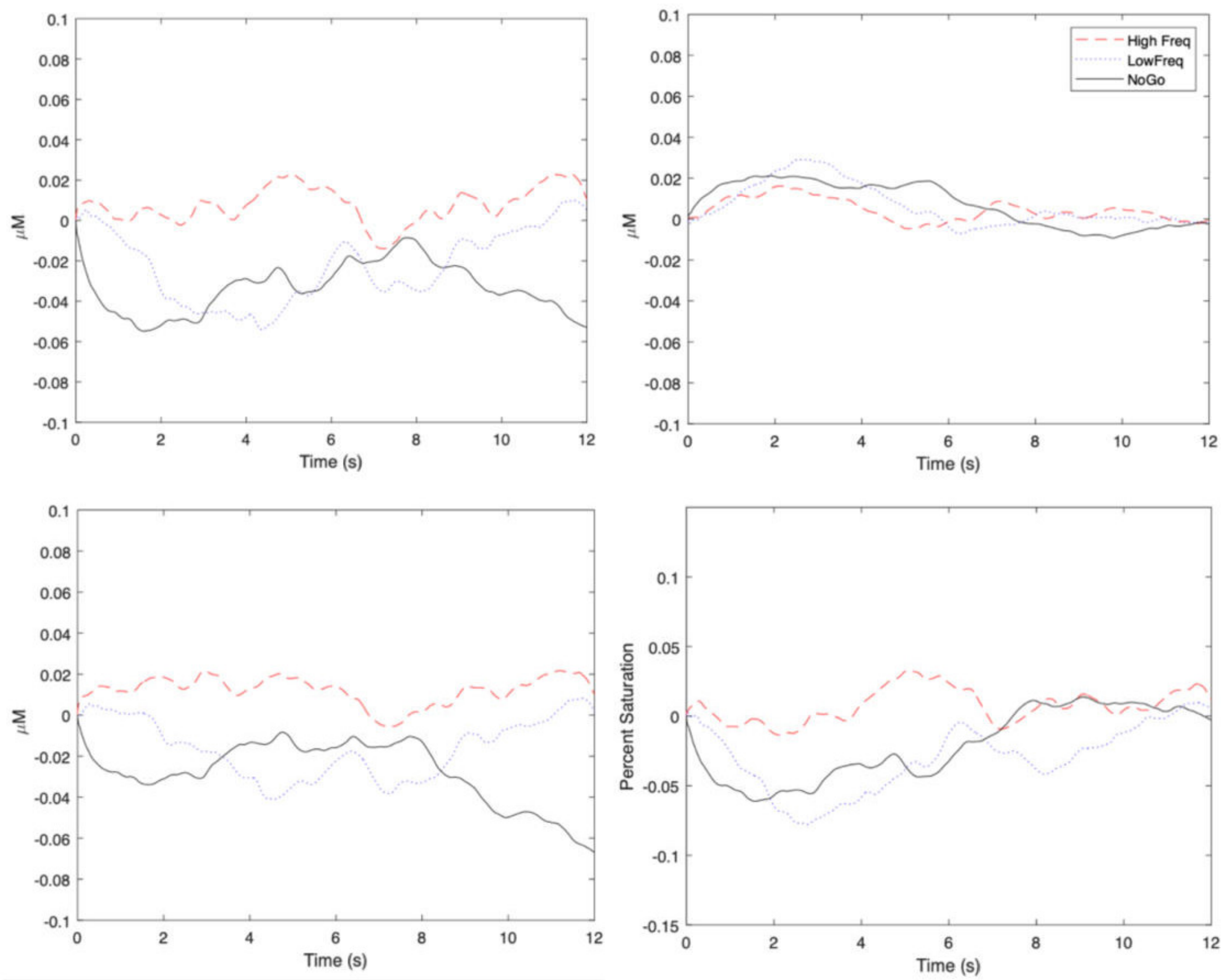

Figure 2. Clockwise, from top-left: NIRS time course data for right PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 1. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

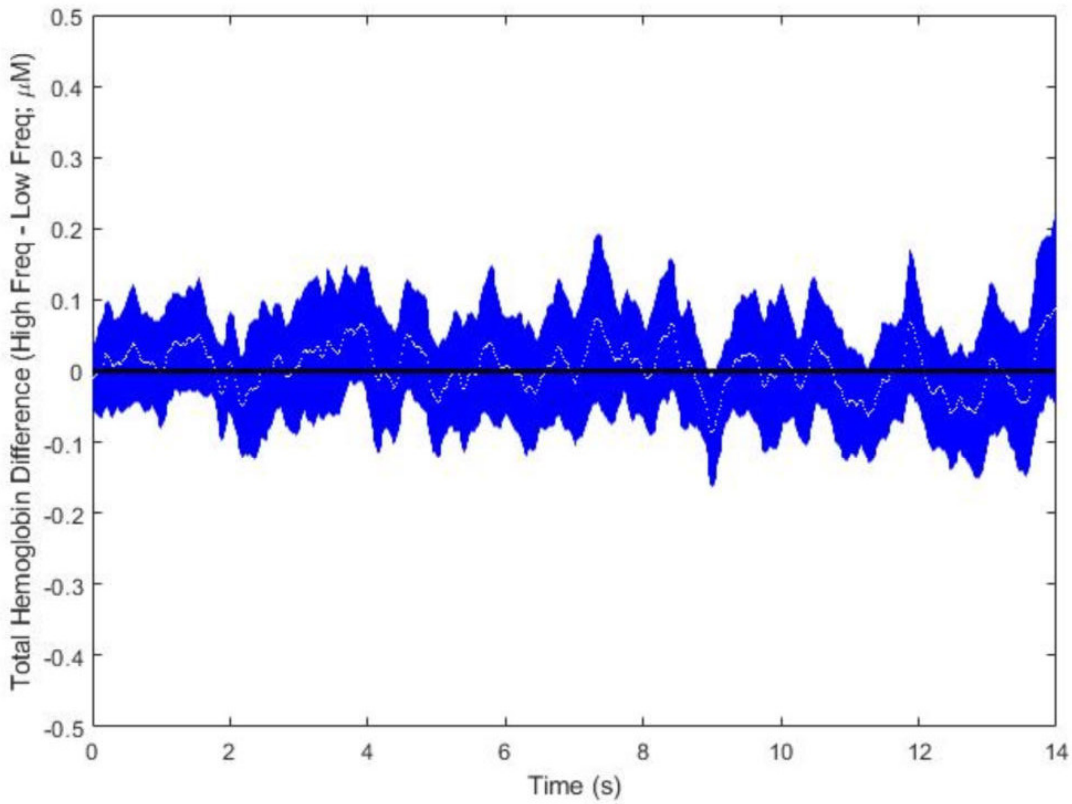

Figure 3. Plotted left hemispheric [THb] difference between high- and low-frequency words for the first 14 seconds following stimulus presentation In Experiment 1. Error bars are Bayesian 99% credible intervals.

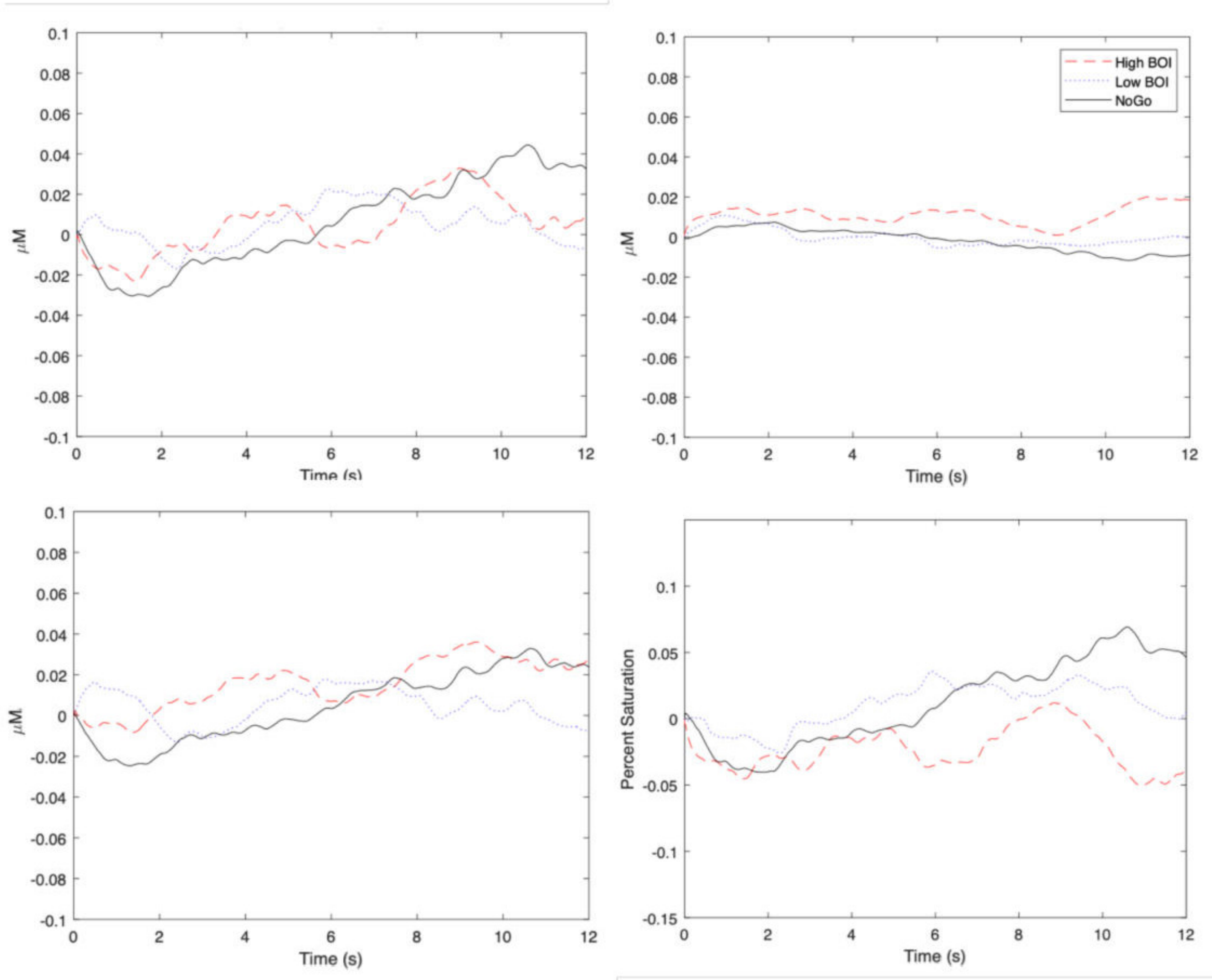

Figure 4. Clockwise, from top-left: NIRS time course data for left PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 2. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

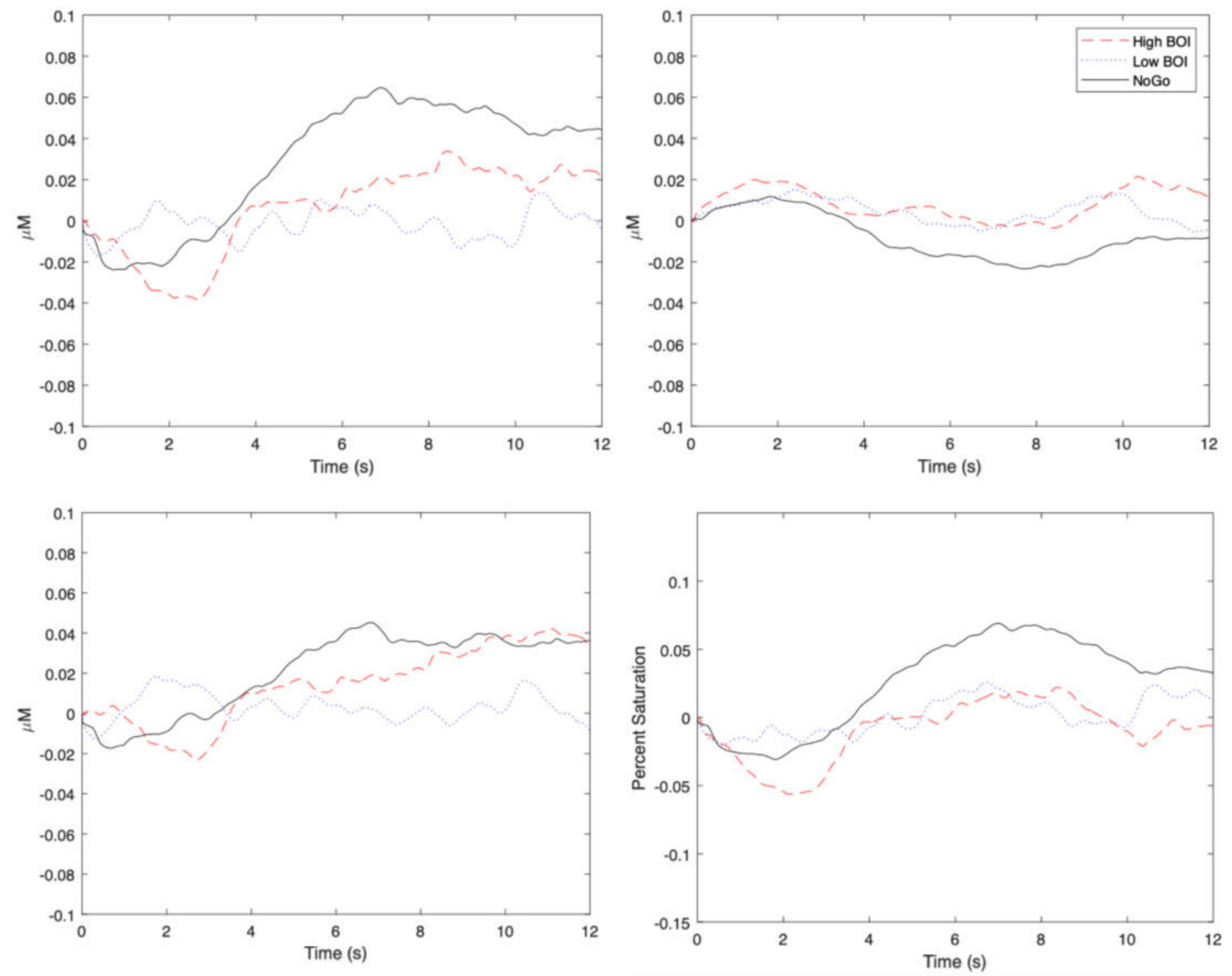

Figure 5. Clockwise, from top-left: NIRS time course data for right PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 2. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

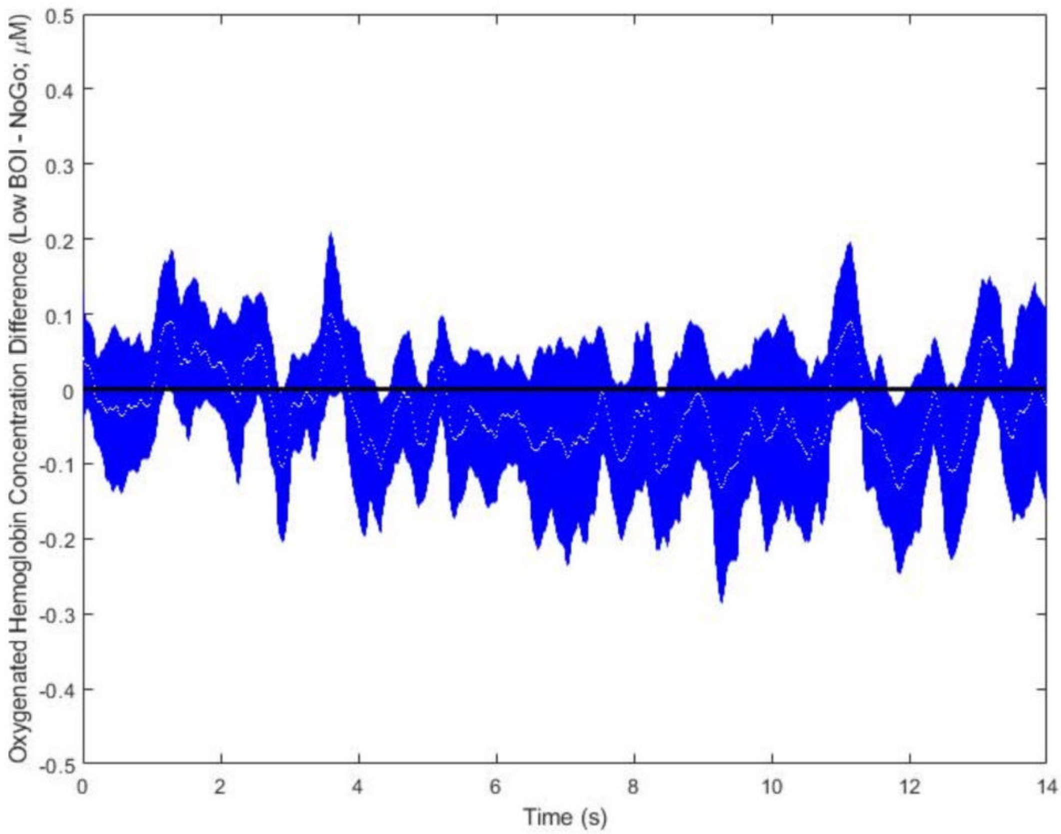

Figure 6. Plotted right hemispheric [O_2Hb] differences between low-frequency words and no-go trials for the first 14 seconds following stimulus presentation In Experiment 2. Error bars are Bayesian 99% credible intervals.

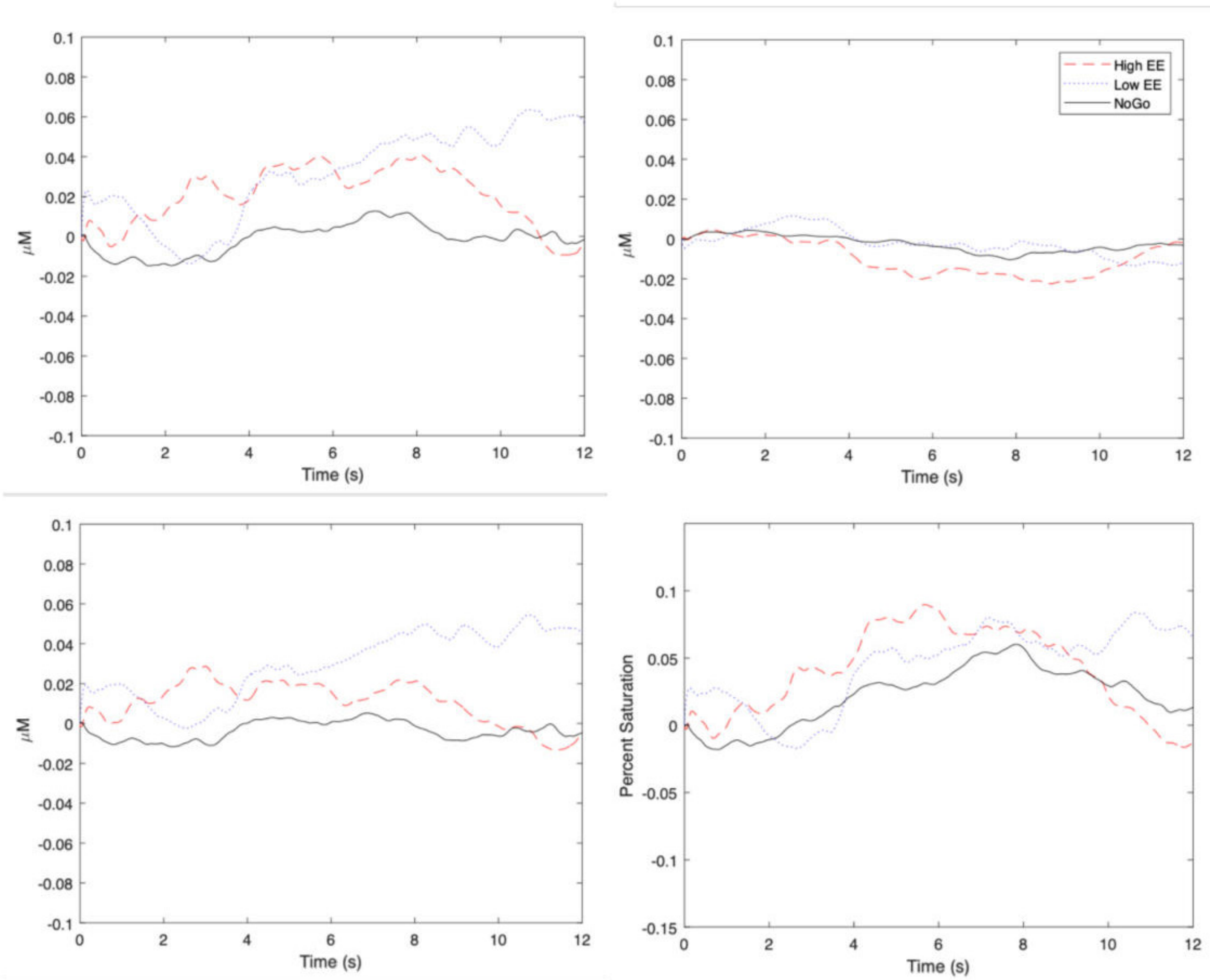

Figure 7. Clockwise, from top-left: NIRS time course data for left PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 3. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

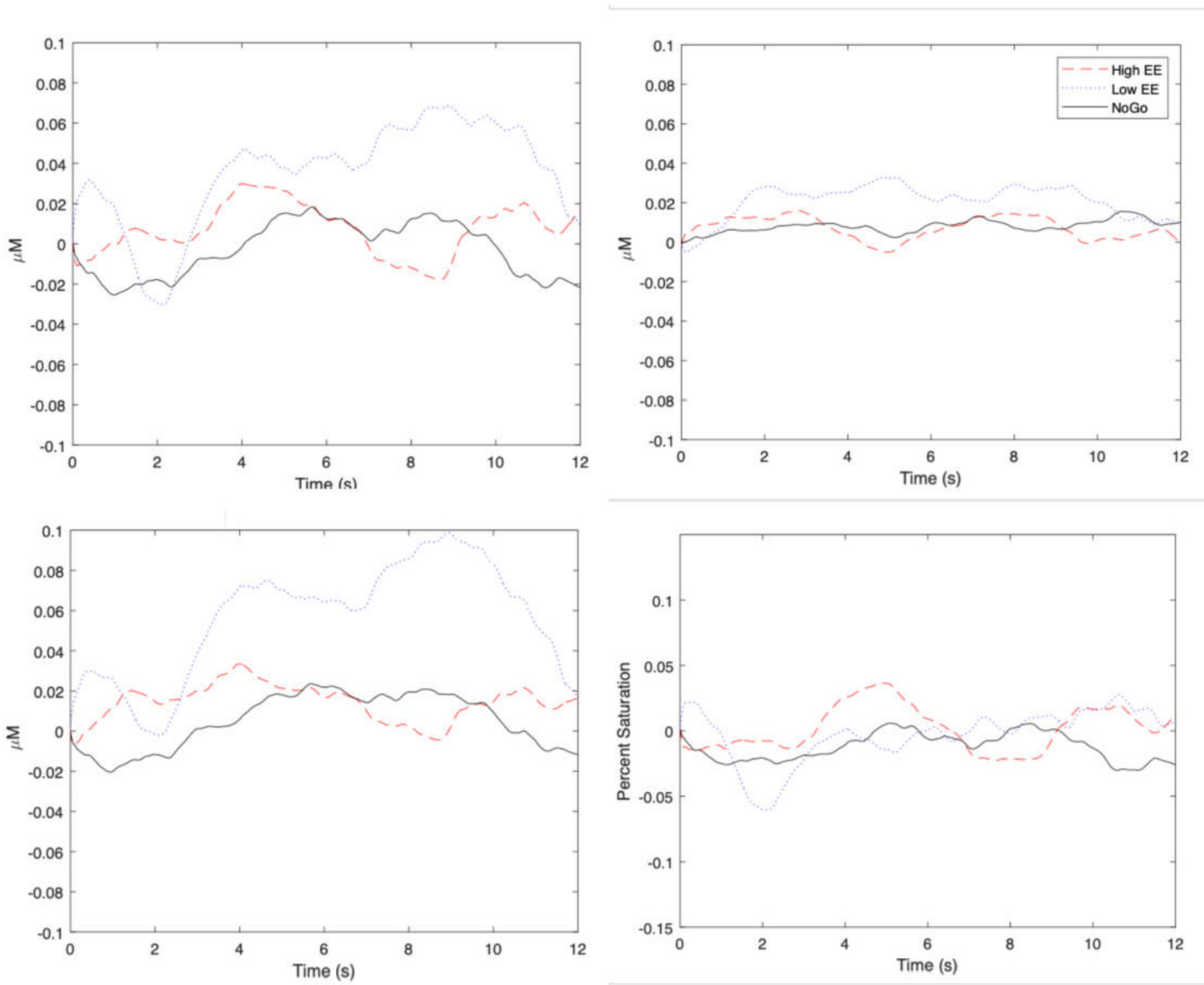

Figure 8. Clockwise, from top-left: NIRS time course data for right PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 3. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

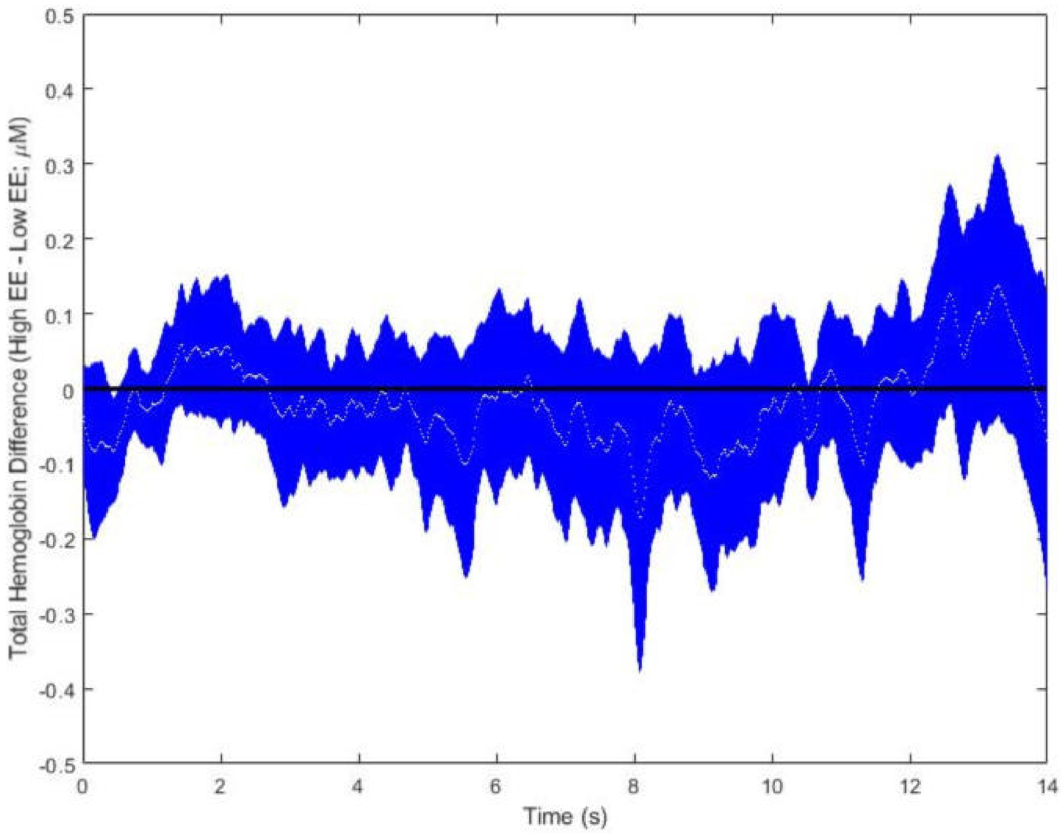

Figure 9. Plotted right hemispheric [THb] differences between high- and low-EE words for the first 14 seconds following stimulus presentation in Experiment 3. Error bars are Bayesian 99% credible intervals.

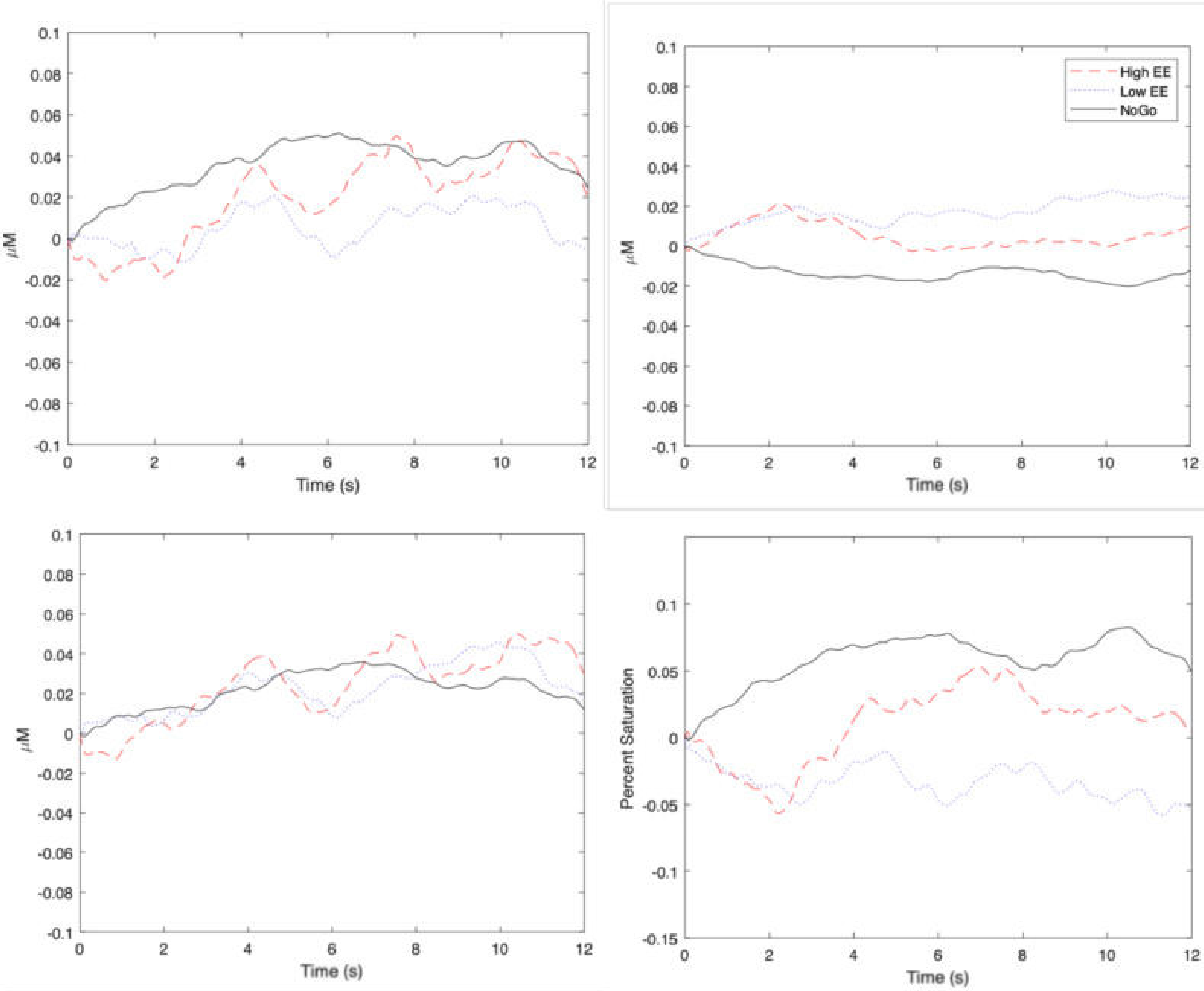

Figure 10. Clockwise, from top-left: NIRS time course data for left PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 4. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

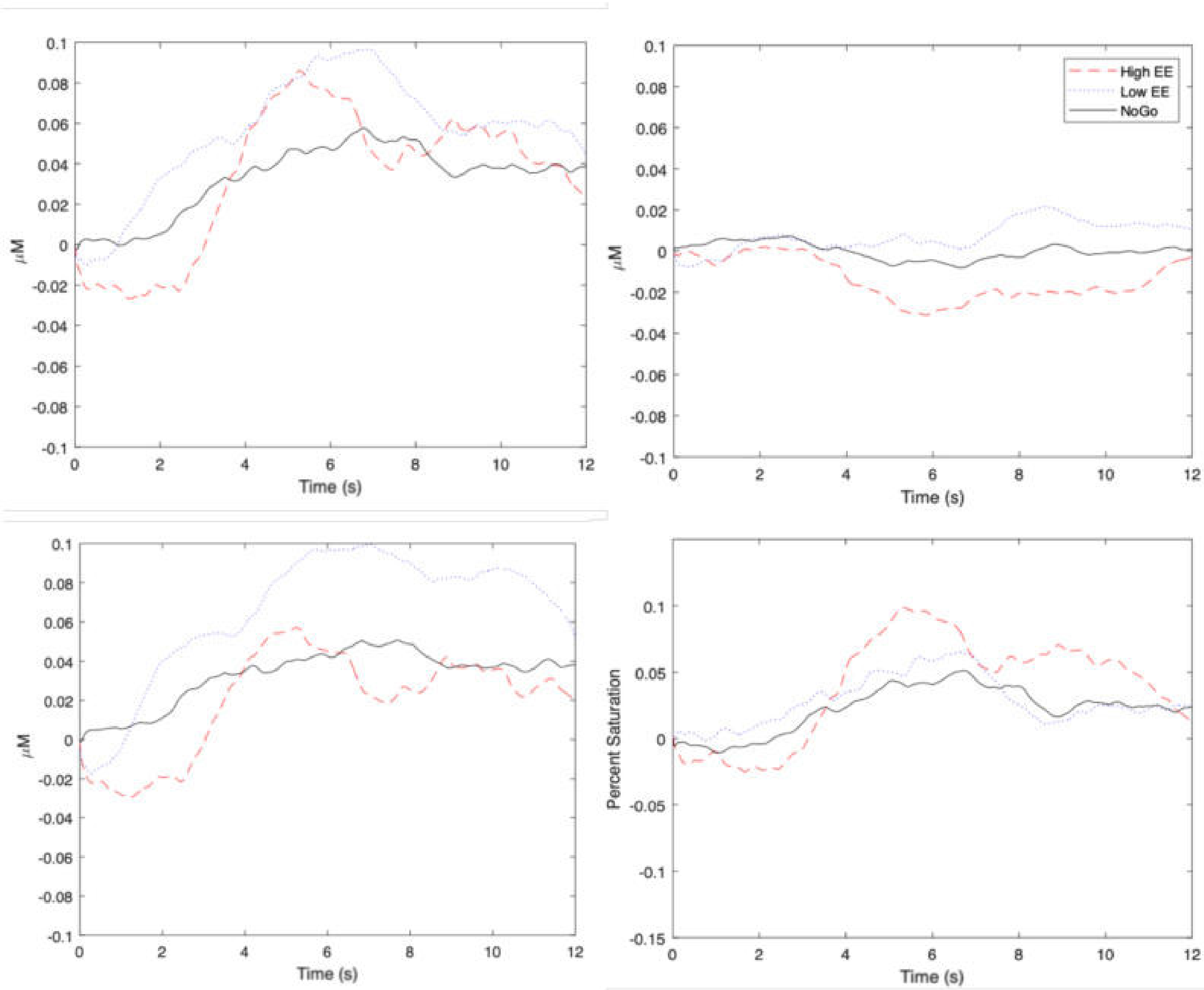

Figure 11. Clockwise, from top-left: NIRS time course data for right PFC [O_2Hb] (μM), [HHb] (μM), [THb] (μM), and Sat% (%) in Experiment 4. Data were cleaned up with a 200 ms average moving window for ease of display and interpretation.

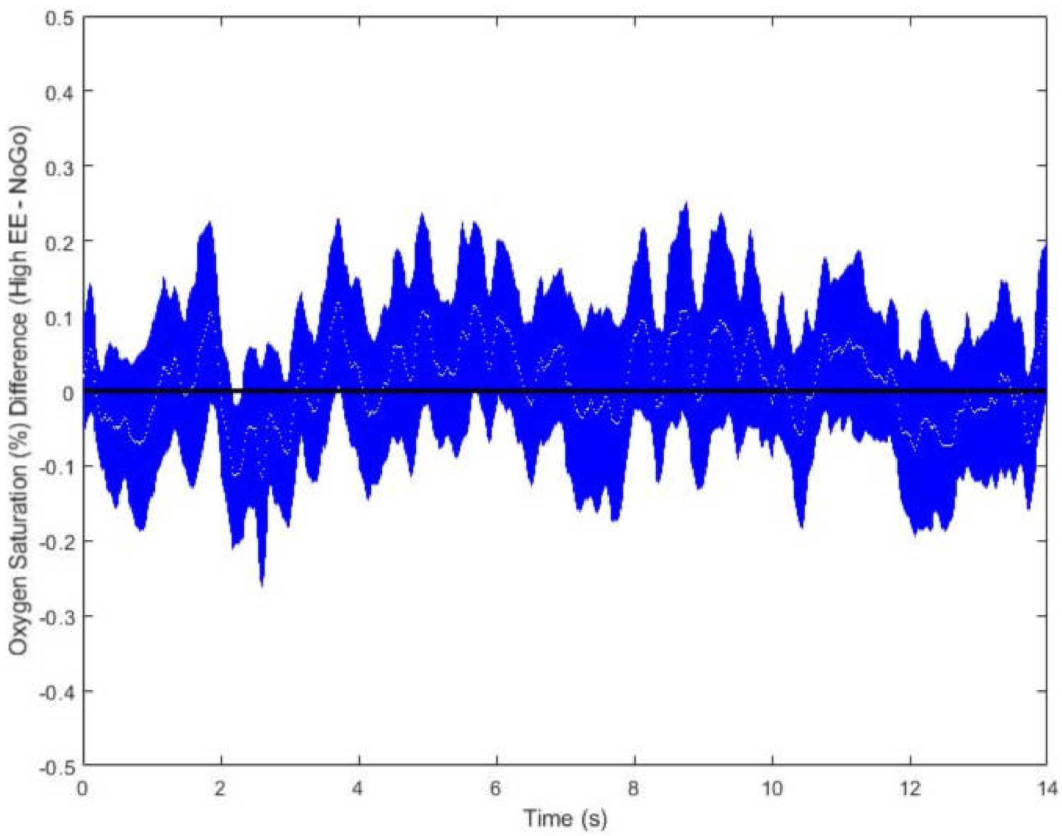

Figure 12. Plotted left hemispheric [O_2Hb] differences between high-EE words and no-go trials for the first 14 seconds following stimulus presentation in Experiment 4. Error bars are Bayesian 99% credible intervals.

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Table 1

Stimuli for Experiment 1

High Frequency	Low Frequency	Non-Words	
ARMY	ATOM	ANID	PANI
AWAY	BACON	BIVER	PEAF
BEGIN	BAKER	BLAVE	PIGE
BOOK	BITE	BOKY	PIPEG
BORN	BLANK	BOUS	PLOSS
BROWN	BLOND	BRAB	POAM
CLASS	BOMB	BULE	POOG
CLAY	BORED	BULP	PORSE
CLEAN	BOWL	CACK	POWN
CLEAR	CALF	CEED	PROKE
DATA	CLUE	CINK	PRONT
DATE	CORK	CLANE	PUNG
DEAL	CRIB	CLEAK	RALT
DOWN	CUTS	CLEE	RASTY
EDGE	DASH	CLIDE	RECK
EYES	DEBT	COOR	RISH
FACT	DEER	CUDDY	RODGE
FAIR	FIRED	DOWED	RONCH
FILM	FISH	FANK	ROUTH
FIRM	FOAM	FRACE	SCOCK
FIXED	FUEL	FREG	SEAX
FOUND	GLAD	FRINT	SENG
FULL	GLOOM	FUMP	SERE
GIVEN	GRADE	GADE	SHEEL
HEART	GRAPE	GAKED	SHILE
KNOW	HUMOUR	GARED	SHYME
LADY	INCH	GICE	SILP
LARGE	JUMP	GINUS	SLAMP
LATER	KNEE	GLODE	SLANK
LIGHT	KNOT	GOUTH	SLARE
LOWER	LEMON	GREE	SLEED
MEAN	LINK	GRIKE	SLET
MEANT	LION	GUNG	SLORE
MONTH	LODGE	HEARY	SLOVE
NIGHT	LOYAL	HEEM	SLOY
NORTH	MILD	HEVER	SLUNT
NOTE	MOUSE	HOAL	SMAT
ORDER	NURSE	HORRY	SNAN
PASS	PATH	JAME	SOAN
PEACE	PEACH	JELT	SOIN
POWER	PINK	JITE	SOLLY
RACE	PITY	JOOT	SOUN

REACH	PLOT	JUNA	SPOW
RISE	PUMP	KEED	SPUT
RIVER	PUSH	KILA	STORN
ROAD	REACT	LENY	TANNY
ROLE	RIDE	LINDER	TELON
SHARE	SCARE	LOLD	TIDDY
SIGN	SHADE	LOMP	TIVID
SIZE	SHIPS	LUSK	TOACH
SORT	SKIN	MALED	TOAR
SOUTH	SPADE	MARER	TRAKE
STAGE	SPAN	METT	TREAK
STAY	SPARE	MOATH	TREST
STOP	SPRAY	MODEO	TRIAR
STORE	STACK	MOEL	TROP
SURE	STEEL	MOOST	TROSS
TALK	STEM	MOUL	TROW
TRUE	SUITE	NAZE	VACED
UNIT	TIRED	NEEP	VACK
VOTE	TOWER	NINCH	VASH
WALK	TREAT	NING	VIRE
WATCH	TWIN	NOAST	VUFF
WHOLE	WARN	NOIL	WAVEG
WORTH	WEAVE	NOVE	WEAG
WRITE	ZERO	PALI	YINK

Note: High- and low-frequency words are balanced on orthographic neighbourhood, number of letters, number of morphemes, number of syllables, and phonological neighbourhood size, and the non-words are matched with all words on length and do not differ significantly in the number of orthographic neighbours.

Table 2

Stimuli for Experiment 2

High BOI	Low BOI	Low Imageability Fillers	
BELT	ASH	WISP	EVE
BOOT	BACK	NODE	NEED
CAGE	BAND	GALE	ROLE
CARD	BAY	PART	WAY
CHILD	BIRCH	SPAN	SPRIG
CORD	BRAIN	CLANK	FRAUD
COUCH	BRASS	FLUX	FIEND
DRILL	CASE	GUISE	WISH
FEET	COAST	REALM	THING
FRIEND	FROST	GAIT	BLOKE
GATE	GAME	STANCE	MODE
HAT	GANG	ZEAL	LODE
HOOK	HEART	LYE	THYME
LAKE	JAIL	HALF	BRIG
LOCK	KING	HOAX	DOSE
MAIL	KNIGHT	RIFT	SCRUFF
MAN	LANE	PEAT	VERB
MAT	LINT	EBB	BANE
MATE	LOOT	NAPE	TERM
NECK	LUNG	DEED	MYTH
PRIEST	PLACE	CHANCE	SHAME
PURSE	PRINCE	STILE	CLINK
ROOM	PUMP	FLAW	ZING
SEAT	ROOF	CUSP	FUNK
SILK	SHOP	WRIT	LUCK
STAIR	SLIT	CHOICE	BULK
STRING	SONG	STEPPE	HYPE
SUIT	SPOT	MOOD	QUIP
SWORD	STRIPE	TREND	GROUCH
THING	SUN	FUGUE	PIP
TOOL	TRAIL	PLOY	TOT
TOY	TAR	WIT	HUNCH
TUBE	WAR	TACT	SLAG
VEST	WELL		
WHEEL	WITCH		

Note: High- and low-BOI words are balanced on length, number of features, familiarity ratings, concreteness, imageability, print frequency, contextual diversity, and Levenshtein orthographic and phonological distances.

Table 3

Stimuli for Experiments 3 & 4

High EE Abstract	Low EE Abstract	High EE Concrete	Low EE Concrete
ADVERSITY	ADVANCE	ARTIST	ALUMINIUM
AFTERLIFE	AMOUNT	BABY	AUDITORIUM
ATROCITY	APPROACH	BEDROOM	BARREL
ATTITUDE	APTITUDE	BULLET	BASEMENT
BELIEF	ARRAY	CHICKENPOX	BASIN
CONCERN	BLANDNESS	COLLEGE	BLACKSMITH
CONTROL	CAPACITY	COMRADE	BUTTER
COURAGE	COMPOUND	CONCERT	CARPET
CRISIS	CUSTOM	COUSIN	CHINCHILLA
DEMOCRACY	DECREASE	DAUGHTER	COLLAR
DESIRE	DEDUCTION	DAYLIGHT	COLUMN
DISCIPLINE	DISPOSITION	DESTROYER	CORNER
DISTRESS	EFFECT	DIAMOND	COTTON
EMANCIPATION	FACILITY	DISEASE	DISHWASHER
ENVY	FEATURE	HURRICANE	DOORWAY
EQUITY	FIGMENT	HUSBAND	ELBOW
FAILURE	FORETHOUGHT	JEWEL	ENGINE
FEELING	HEREDITY	LAUGHTER	ENVELOPE
FUTURE	HOUR	LEADER	FABRIC
JUDGEMENT	HYPOTHESIS	LION	FINGER
JUSTICE	ILLUSION	MISTRESS	FRECKLES
MIRACLE	IMAGE	MONSTER	HELMET
NEGLECT	INCLINE	MOUNTAIN	HIGHWAY
OFFENCE	INSTANT	NAVY	HOTEL
OPPORTUNITY	MANNER	PARTNER	JACKET
PATIENCE	METHOD	PENICILLIN	KITCHEN
RELIEF	NONSENSE	PICTURE	MERCHANT
REVENGE	NOTHING	POLICE	NUMBER
SOBRIETY	PARDON	SCHOLAR	PITCHER
SOUL	RATING	SERVANT	PROJECTOR
SUPPORT	REVIEW	SHERIFF	QUARTER
SUPPRESSION	TENDENCY	STUDENT	RECTANGLE
TRUTH	TRIFLE	SUMMER	SANDWICH
VALUE	UPKEEP	TUBERCULOSIS	SCREWDRIVER
WEAKNESS	VENTURE	WINTER	STATION

Note: High- and low-EE words are balanced within concrete and abstract word categories on log HAL frequency, age of acquisition, orthographic neighbourhood, number of letters, number of syllables, number of morphemes, concreteness, and imageability.

CHAPTER 4:

Electrophysiological Evidence of Automatically Activated Grounded Semantic Knowledge

Experimental findings show differential event-related potential (ERP) patterns (either quantitatively in a deflection's magnitude at a single electrode, or qualitatively with regard to the topology of brain activity across multiple electrodes) depending on task demands, illustrating its usefulness in identifying and testing the neurological markers of human cognition (e.g., Barber, et al., 2013; Kutas & Hillyard, 1980). As mentioned in Chapter 2, electroencephalography (EEG) is a technology with excellent temporal resolution which makes it ideal for observing fast cognitive processes such as language processing (Hauk, 2016). More specifically, responding to word stimuli requires rapid identification of the orthography of the presented letters and activation of associated semantic information before making a response, which is typically done in less than one second (Hargreaves & Pexman, 2014; Laszlo & Federmeier, 2014). Hauk (2016) outlined the necessary cognitive processes that precede responding as follows: visual processing, lexical and semantic long-term memory retrieval, working memory processing, and response selection. Eye-tracking data suggest that words are recognized as unique entities within 100-150 ms after presentation (Laszlo & Federmeier, 2014). With so many cognitive processes happening in such a short period of time, investigating the time course of grounded cognition in semantics requires a technology that is capable of monitoring these processes as they happen in real time. Although there is some debate regarding how to discuss ERP components as discrete entities (Luck, 2014), there are characteristic patterns of ERP deflections in semantic processing experiments that can be investigated.

Previous research has attempted to illustrate the time course of semantic processing, though the results have yet to produce a coherent picture of what dimensions are processed in what order and under which conditions. When single words are used as experimental stimuli, the earliest reliable effects have been observed within 100-150 ms after stimulus presentation. Using a signal-to-respond methodology, Hargreaves and Pexman (2014) observed behavioural facilitation for the number of senses evoked by a word after 100 ms of word processing. Using ERP methods, Kuchinke and Mueller (2019) observed differences in the P1 and N1 (peaking 100-130 ms after stimulus presentation) for emotional words. Similarly, higher P100 magnitudes have been observed in parieto-occipital regions for emotion-laden words, suggesting a very early stage in word processing that is sensitive to emotional information, particularly when that information is negative (Wang, et al., 2019; Zhang et al., 2014). Using regression analyses, Laszlo and Federmeier (2014) showed superior statistical prediction of the first 50 ms of ERP data in visual word recognition with models that include the influence of lexicality and of the first 120 ms with models that include the influence of semantics. Furthermore, the topography of brain responses has been observed to differ between word categories as early as 100 ms after stimulus presentation (Mosely et al., 2013). Collectively, these findings suggest that the brain's processing of word stimuli is well underway by 100-150 milliseconds after stimulus presentation, with some evidence of semantic sensitivity at that time.

By 200 ms after stimulus presentation, the influence of semantic information on ERP patterns is reliably observed (Clarke, 2020). A word's imageability has been found to modulate ERP components prior to 250 ms after stimulus presentation (Hauk, 2016). The P200 peaks between 150 and 275 ms after stimulus presentation, and greater amplitudes have been observed for words with greater levels of emotion information, especially with negatively valanced words (González, et al., 2014; Kanske & Kotz, 2007). P200 amplitude is also greater during poor memory performances (i.e., recalling fewer items), and when processing sentences with semantically constrained endings (e.g., Federmeier & Kutas, 2002; Freunberger, et al., 2007). The P200 has also been shown to be sensitive to noun/verb distinctions and to be enhanced for emotion-laden words (Yudes, et al, 2016). Additionally, the P200 has been shown to be enhanced when processing words with more associated concepts (Stuellein et al., 2016). The P200 reflects both the amount of experience with a word's referent and the amount of effort required to process stimulus ambiguity (Wang et al., 2019).

Many of the most well-known semantically-associated ERP components peak between approximately 300 ms and 500 ms after stimulus presentation, the most common of which is the N400 component. The N400 was first observed to be amplified in response to the last word in a sentence *if* that word was unexpected (e.g., "he takes his coffee with cream and *bananas*"; Kutas & Hillyard, 1980; Van Petten, et al., 1999). The N400 has since been found to be amplified by unexpected faces and pictures (Lau, et al., 2008). Greater N400 amplitudes have been observed to individual words possessing many semantic features or associated concepts (Vegara-Martínez et al., 2017). N400 amplitudes are typically decreased in response to familiar or contextually supported stimuli, and even in response to repeated non-word or pseudoword stimuli (Lau et al., 2008; Laszlo & Federmeier, 2014, Stuellein et al., 2016; Vegara-Martínezet et al., 2017). These data suggest that the N400 does not exclusively reflect semantic processes. Rather, it could be interpreted as reflecting either contextual integration between stimuli and task demands or the effort to retrieve contextually relevant memories (Lau et al., 2008).

The N400 may not be a single component, making it difficult to interpret. Rather, the N400 may reflect many processes that occur at the same time (an interpretation that is supported by difficulty to localize a single N400 generator in the brain; Lau et al., 2008). N400 amplitude is inconsistently influenced by semantic richness. For example, the N400 is attenuated when processing emotion words (e.g., Kanske & Kotz, 2007; Kotz & Paulmann, 2007; Wang et al., 2019), yet is larger in response to action than to non-action words (Yudes et al., 2016). Conversely, more extreme N400 amplitudes have been observed by 370 ms for emotion words in LDTs, but as early as 170 ms in semantic contexts (Schact & Sommer, 2009). The differential ERP time course in different tasks using emotion information as the manipulated semantic dimension suggests feed-forward processing in which an individual is primed to process or attend to particular types of information depending on context.

Beyond the N400 window, semantic effects have been observed in what is called the late positive component (LPC) and the P600 (Coulson et al., 1998; Gouvea et al., 2010). The LPC has been found to be largely sensitive to emotion information, leading to an interpretation that it reflects additional sustained evaluative processing (Kurchinke & Mueller, 2019; Wang et al., 2019). The P600 has been referred to as the ‘syntactic positive shift’ and is thought to be elicited by word stimuli that require reanalysis (Coulson et al., 1998; Gouvea, et al., 2010). ERP components this late after stimulus presentation are likely reflective of post-lexical processing that does not contribute directly to the contextual identification of a presented stimulus. Some stimuli, being more ambiguous due to having lower levels of semantic richness than others, require extended processing even after lexical processes related to a word’s meaning are completed. All other information about a presented word stimulus has been activated and processed previously in the first ~500 ms after stimulus processing.

Some ERP research has been done on semantic richness, specifically. For example, in a SCT using word pairs as stimuli, and decision criterion of, “Is the second word an example of the first?”, smaller N400 deflections were observed for typical exemplars (i.e., “yes” responses), and when the word pairs were semantically related, regardless of category membership (Heinze et al., 1998). This result demonstrates that N400 amplitudes are associated with the activation of a word's meaning.

The N400 has also been tied to embodied semantic processing and language comprehension (e.g., Blomberg et al., 2020; Xue et al., 2015). In an LDT, Blomberg et al. (2020) measured ERP data for four different noun categories: specific concrete (e.g., hammer), general concrete (e.g., tool), abstract (e.g., reason), and emotional abstract (e.g., love). N400 amplitudes were most negative for specific concrete nouns, followed by general concrete nouns, abstract nouns, and finally by emotional abstract nouns. These data show that the N400 is modulated by many variables including the specificity and amount of emotion information associated with a concept's representation. Xue et al. (2015) measured ERPs to the last word of a visually presented sentence using stimuli that varied in body-object interaction ratings (BOI) in a sentence acceptability task. The target words were either rated high or low in BOI and were presented after either a semantically rich sentence (i.e., possessing at least one associated sensorimotor property) or a semantically poor sentence (i.e., possessing only a description of the word). Regardless of sensorimotor context, high BOI words were responded to more quickly and sentences ending in high BOI words were judged as more acceptable than those sentences ending in low BOI words. High BOI words produced smaller N400s than did low BOI words at central and parietal locations, particularly when high BOI words were presented in semantically poor contexts (e.g., "you brush pieces of a baked *crumb*") versus semantically rich contexts (e.g., "you brush the small sticky *crumb*"). In an object recognition experiment, less pronounced N400 deflections were observed in the anterior temporal lobe when the target object was primed by the presentation of a word or picture depicting an object that could be manipulated in the same way as the target object (Kiefer et al., 2011). This finding suggests that N400 amplitude does, in fact, reflect semantic processing rather than lexical processing. In sum, higher levels of semantic richness interacted with context and produced ERPs that reflected the amount of effort required to interpret the words contextually, such that N400 amplitude was greater for words with higher levels of semantic richness, yet comparatively lower when semantically rich words were contextually integrated more easily.

Given the findings summarized above, ERP data may allow researchers to observe when lexical and semantic information is processed. Such an approach is capable of demonstrating distinctly different patterns of neural activity produced by the manipulation of grounded semantic richness variables. As such, regardless of where in the brain a particular ERP component originates, if the manipulation of grounded semantic variables (e.g., BOI and EE) produces ERP differences (e.g., magnitude, scalp distribution, and/or timing) conclusions may be made regarding the relative automaticity and contribution of grounded cognition dimensions to semantic processing. Amodal theories of cognition, by comparison, struggle to adequately explain such observations, particularly if the effects were evident very early in the course of processing or in tasks where grounded semantic information is not explicitly required for successful task completion. By analyzing the time course of ERPs after single word presentation, it is possible to elucidate the intrinsic and automatic nature of grounded semantic information in conceptual processing.

In the research presented below, several behavioural and neurological predictions regarding the effects of grounded semantics in three SCTs were tested. EEG was employed in three experiments to investigate whether there are differential patterns of response latencies and neurological activity during SCTs wherein grounded semantic information is not explicitly relevant for task completion.

In Experiments 2 and 3, high levels of the dimensions of grounded semantic richness and emotional experience (BOI and EE) were congruent with the decision criteria, “Is this word easily imageable?” and, “Is this an abstract noun?” respectively. As such, higher levels of grounded semantic richness are predicted to be facilitatory and thus produce shorter response latencies and attenuated ERP amplitudes due to the congruence between the nature of the semantic information and the decision criteria. In Experiment 4, however, high levels of the dimension of grounded semantic richness (EE) were incongruent with the decision criterion, “Is this a concrete noun?” As such, high levels of grounded semantic richness are predicted to be inhibitory and to produce longer response latencies and greater ERP magnitudes due to the incongruence between the decision criterion and the nature of the semantic information (EE).

Hypotheses

Experiment 2 tested the grounded cognition hypothesis that semantically rich words (operationalized here as words with referents associated with greater amounts of bodily experiences and interactions) are processed more efficiently than less semantically rich words (operationalized here as those with referents associated with comparatively fewer bodily experiences and interactions). This experiment employed a modified version of the go/no-go SCT used by Hargreaves et al. (2012), with the decision criterion, “Is this word easily imageable?” All stimuli requiring a button press (i.e., the “go” trials) were highly imageable, and half of the highly imageable words were rated high in BOI, whereas the other half were rated low in BOI. It was predicted that, compared to words rated low in BOI, words rated high in BOI would be responded to more quickly, more accurately, and would produce discernibly different ERPs. These differences were predicted due to the relative ease of processing and the increased number of sensory and motor brain regions thought to be responsible for the processing of words with greater amounts of contextually congruent grounded motor semantic richness. Specifically, the P200 component was predicted to be larger for words rated low in BOI due to their lower levels of grounded motor semantic richness, which would lead to their being more difficult to process due to their contextual ambiguity as imageable nouns. Similarly, the N400 was predicted to have lower amplitudes for words rated high in BOI due to their contextual relevance (words that one has interacted with frequently are also likely to be seen frequently, thus facilitating an 'imageable' response). The later components (P600/LPC) were predicted to have higher amplitudes for words rated low in BOI due to the increased probability that these stimuli warrant more processing as atypical exemplars of imageable nouns. In sum, an imageable concept with low BOI ratings will be more difficult to identify as imageable and thus require additional processing in the later stages.

Experiment 3 tested the grounded cognition hypothesis that abstract nouns with referents with greater levels of associated emotion experiences are processed more efficiently than abstract nouns with lower levels of associated emotion experiences. Specifically, abstract concepts are hypothesized to be understood more quickly and accurately when they are associated with more emotion experiences. Experiment 3 used a SCT with the same decision criterion as Newcombe et al. (2012), with the addition of EEG observations to investigate the neural activity correlated with processing varying levels of emotion information while identifying abstract nouns. The decision criterion for the SCT was, "Is this an abstract noun?" As such, participants were to respond to abstract nouns and to make no response to concrete nouns. Half of the abstract nouns were rated high in EE and thus thought to be more 'typical' exemplars of abstract nouns. It was predicted that words rated high in EE (greater grounded semantic richness obtained through emotion experiences with the words' referents) would be responded to more quickly than those rated low in EE, while also producing discernibly different ERPs reflecting the congruency between of emotion information and the decision criterion. The other half of the abstract nouns, rated low in EE, were hypothesized to be more difficult to process as abstract nouns due to their comparative lack of diagnostic EE information. Similar to Experiment 2, it was predicted that the P200 would be smaller for words rated high in EE because they are typical exemplars of abstract nouns, and thus comparatively easier to process. The N400 was also predicted to be smaller for words rated high in EE due to comparative ease to integrate these stimuli into the context of the decision criterion due to congruence between EE and task demands, and the P600/LPC would be larger for words rated low in EE because these words are atypical exemplars of abstract nouns.

Experiment 4 tested the hypothesis that the activation of grounded information is an automatic part of conceptual knowledge, regardless of its task relevance. Specifically, by employing the same stimuli as Experiment 3 but with the SCT decision criterion, "Is this a concrete noun?" participants would be responding to concrete nouns with high and low EE. Concrete nouns have, by their nature, physical referents that are easily perceived and many may be relatively easily physically interacted with, but typically have fewer associated emotion experiences (see Table 1 in Newcombe et al., 2012 to compare EE ratings of concrete and abstract nouns, noting that concrete nouns have significantly lower EE ratings). As such, it was hypothesized that concrete nouns rated high in EE would be atypical concrete nouns, because the additional grounded semantic richness obtained through emotion experiences would be more diagnostic of abstractness than of concreteness. It is predicted that response latencies to concrete nouns rated high in EE will be *slower* compared to more typical concrete nouns rated low in EE. This hypothesis is congruent with previous research (e.g., Newcombe et al, 2012) that observed lower accuracy rates for concrete nouns rated high in EE and is important for the following reasons. If supported, the hypothesis that concrete nouns rated high in EE would be atypical would suggest that grounded semantic richness need not always be facilitatory to successful task completion. Moreover, if participants respond more slowly to concrete nouns rated high in EE, it would suggest that grounded semantic richness is activated automatically when reading a word, regardless of whether the specific semantic information is congruent (and thus advantageous) to current task demands. Observing slower response latencies to concrete nouns rated high in EE would contribute to addressing the question of *how* conceptual knowledge is processed in the brain. If the grounded PSS framework is correct, then this processing of conceptual knowledge should entail an automatic reactivation of the sensory, motor, and emotion experiences that are commonly associated with that concept's real-world referents. As a result, it is predicted that the P200 for concrete nouns rated high in EE will be larger due to the additional effort needed to process atypical concrete nouns. The N400 is predicted to be larger for concrete nouns rated high in EE due to the contextual incongruence between task demands and the diagnostic nature of the semantic information being activated. Finally, the P600 is predicted to be larger for concrete nouns rated high in EE due to the reanalysis of atypical concrete noun exemplars.

Summary of Hypotheses. In sum, participant response latencies were predicted to be shorter and accuracy rates higher when responding to word stimuli that were rated high in task-congruent grounded semantic richness (Experiments 2 and 3). Conversely, participant response latencies were predicted to be longer and accuracy rates lower when responding to word stimuli that were rated high in task-incongruent grounded semantic richness (Experiment 4). In Experiments 2 and 3, lower P200, N400, and P600 amplitudes were predicted for word trials with high grounded semantic richness because of the comparative ease of processing due to the grounded semantic richness's task congruence. In Experiment 4, however, larger P200, N400, and P600 amplitudes were predicted for word trials with high grounded semantic richness because, in this experiment, the grounded semantic richness (EE) was not congruent with task demands.

Method

Participants. Three separate groups of 25 University of Northern British Columbia undergraduate students enrolled in psychology classes participated in each experiment (i.e., no individual participated in more than one experiment). There were 19, 18, and 19 female participants in Experiments 2, 3, and 4, respectively. Participants indicated that they were native English speakers and had normal or corrected-to-normal vision. Participants received bonus course credit for their participation.

Apparatus.

Behavioural. Behavioural data were collected with Superlab (version 5.0.3). Stimuli were presented in white 24-point capitalized Times New Roman font centred on a 21.5” Dell P2212H monitor on a black background. Participants were seated in front of a table so that they could reach the keyboard, see the monitor, and remain comfortable for the duration of the experiment.

EEG. Electrical brain activity was recorded at 250 Hz with a 32-channel EGI HydroCel Geodesic sensor net with silver-silver chloride electrodes (Magstim EGI, Eden Prairie, MN). Two cap sizes were available (54-56 cm and 56-58 cm). Participants whose heads did not fit either cap were given course credit but did not participate further in the experiment. EEG data were captured with EGI’s Net Station Acquisition software (version 5.2.0.1).

Semantic Categorization Task. The SCTs for all three experiments are fully detailed in Chapter 2.

Analyses.

Data Preprocessing. Data preprocessing occurred in the following manner. First, any participant with an error rate exceeding 30% was removed from the data sets (one participant from Experiment 2, two participants from Experiment 3, and no participants from Experiment 4). Second, any word that was responded to incorrectly in more than 30% of the instances of its presentation across participants was removed from all analyses (eight items from Experiment 2: one high-BOI word and seven low-BOI words, 6.1% of the data; five items from Experiment 3: five low-EE words, 3.5% of the data; and eight items from Experiment 4: seven high-EE words and one low-EE word, 5.7% of the data). Incorrect responses were then removed from all further behavioural or EEG analyses (392 trials from Experiment 2 (12.4% of the data); 364 trials from Experiment 3 (11.3% of the data); and 332 trials from Experiment 4 (10.2% of the data). Response latency outliers were identified and removed from all analyses if they were faster than 250 ms (no trials from any experiment were removed in this way) or slower than 2000 ms (22 trials from Experiment 2: < 0.01% of the data; 71 trials from Experiment 3: 0.02% of the data; and 26 trials in Experiment 4: <0.01% of the data). Then, for each participant, response latencies greater than 2.5 standard deviations from the cell mean of each condition were removed from all analyses (17 trials from Experiment 2: <0.01% of the data; nine trials from Experiment 3: <.01% of the data; and 18 trials from Experiment 4: <0.01% of the data. From the remaining data, average response latencies for high- and low-BOI stimuli (Experiment 2), and high- and low-EE stimuli (Experiments 3 and 4) were calculated for each participant and then averaged across participants. Separately, average response latencies were calculated for each single word for item-level analyses. Averages were tested using Bayes Factors (BayesFactor; R, version 3.5.3).

EEG. EEG data were analyzed with the EEGLAB toolbox for MATLAB (Delorme & Makeig, 2004). First, the data were digitally band-pass filtered between 0.2-50 Hz. Next, bad channels were identified by visual inspection and then interpolated using the spherical interpolation method. Then time course data were separated into single-trial epochs, baseline corrected to the mean of the 100 ms prior to stimulus presentation, for 800 ms after stimulus presentation. Trials were then flagged if they contained artifacts (identified as deflections that exceed a voltage threshold of 100 μV). Participants with more than 50% of trials removed this way were omitted from EEG analyses (11 participants were removed from Experiment 2, six from Experiment 3, and nine from Experiment 4).

Within-subject condition means (high- and low-BOI, Experiment 2; high- and low-EE, Experiments 3 and 4) were calculated for each participant by taking the average of each 4 ms time point across all trials of each condition type for the 800 ms following each stimulus presentation. Then these within-subject means were averaged across participants, creating a single 800 ms averaged ERP for each condition. Next, an 800 ms difference wave was calculated by subtracting the value of the low condition from the value of the high condition, for each experiment, at each 4 ms time point.

As per Nathoo, Kilshaw, & Masson (2018), within-subject 99% Bayesian credible intervals were then calculated for each 4 ms time point across the entire 800 ms difference wave. This procedure evaluates the strength of the evidence, across time, for a model that allows for the cerebral activity difference between conditions at each 4 ms time point to be different from zero. At any point in time, if the credible interval range does not include zero, then it can be assumed that a model that includes the independent variable (in the present studies, either BOI or EE) is better than a model that does not include the independent variable. The timing and direction of the observed difference can then be interpreted in the context of the original ERP components.

Results

Behavioural.

Statistical Analysis. Comparisons of response latency differences were analyzed using the ttestBF function from the BayesFactor package in R (Morey & Rouder, 2011; R Core Team, 2013). This function produces a statistic (Bayes factor) representing the strength of a model where the two groups' means are assumed not to be zero compared to a model representing a null hypothesis that both groups' data come from the same normal population. Decision-making criteria for 'significance' in Bayes factor analyses are often set between 3 (deemed 'anecdotal evidence') and 10 (deemed 'strong evidence'; Aczel et al., 2017).

Experiment 2. The average within-participant response latencies were 1045.66 ms (SE 38.21 ms) for words rated low in BOI and 932.37 ms (SE 36.27 ms) for words rated high in BOI. The average between-item response latencies were 1038.09 ms (SE 20.00 ms) for words rated low in BOI and 931.40 ms (SE 11.55 ms) for words rated high in BOI.

The Bayes factor was 1,586,393 for the within-participant analysis, and 937.31 for the between-item analysis. The within-participant analysis provides very convincing evidence that response latencies are best predicted by a model that accounts for BOI than one that does not, with high-BOI words being responded to more quickly than low-BOI words. The between-words item analysis provides very convincing evidence that response latencies are best predicted by a model that accounts for BOI, with high-BOI stimuli producing faster response latencies across participants than did low-BOI stimuli.

Experiment 3. The average within-participant response latency was 1255.00 ms (SE 45.71 ms) for words rated low in EE, and 1139.56 ms (SE 40.16 ms) for words rated high in EE. The average between-item response latencies were 1227.56 ms (SE 17.75 ms) for words rated low in EE, and 1126.21 ms (SE 13.43 ms) for words rated high in EE. The Bayes factors were

17,444.18 for the within-participants analysis of response latencies differences, and 949.76 for the between-item analysis. The within-participant analysis provides very convincing evidence that response latencies are best predicted by a model that accounts for EE than one that does not, with high-EE words being responded to more quickly than were low-EE words. The between-words item analysis provides very convincing evidence that response latencies are best predicted by a model that accounts for EE, with high-EE stimuli producing faster response latencies across participants than did low-EE stimuli.

Experiment 4. The average within-participant response time was 977.72 ms (SE 21.36 ms) for concrete words rated low in EE, and 1040.11 ms (SE 28.33 ms) for words rated high in EE. The average between-item response latencies were 980.98 ms (SE 13.54 ms) for words rated low in EE, and 1040.55 ms (SE 25.83 ms) for words rated high in EE.

The Bayes factor was 151.34 for the within-participant analysis, and 4.75 for the between-item analysis. The within-participant analysis provides convincing evidence that response latencies are best predicted by a model that accounts for EE than one that does not, with low-EE concrete words being responded to more quickly than were high-EE concrete words. The between-words item analysis provides some evidence that response latencies to concrete nouns are best predicted by a model that accounts for EE, with low-EE concrete nouns producing faster response latencies across participants than did low-BOI stimuli.

Electroencephalography.

Experiment 2. A full-scalp view of the electrode placements used across all three experiments is presented in Figure 13. Individual ERP waveforms for all electrodes are presented in Figure 14. Figure 15 depicts a full-scalp topography of ERP polarity across time. The ERP waveform resulting from this task is characterized by four distinct components. In chronological order, there is first an early positive deflection evident approximately 100-200 ms after stimulus presentation that appears in all but the centre-most electrodes. This is most likely a P200 component reflecting initial task processing, with condition differences at this time being illustrative of task difficulty. Second, a negative component is evident between 200 and 420 ms after stimulus presentation that is visible in all but the centre-most electrodes, but most pronounced in parieto-occipital locations. This activity is evident earlier for words rated low in BOI and is more pronounced in the left hemisphere (Figure 15). This is most likely a N400 component reflecting the integration of stimuli with current task demands with greater amplitudes at this time reflecting increased integration difficulty. Third, a long positive deflection is evident beginning as early as 300 ms after stimulus presentation and extending past the 800 ms window in some electrodes. This deflection is primarily observable bilaterally in electrodes in temporal and occipital regions, though it is more prominent in the right hemisphere. This is likely a P600 or LPC and is reflective of re-evaluation of stimuli, with greater amplitudes suggesting increased processing for atypical exemplars. Finally, a small number of more central electrodes show a relatively flat, if not negative, component from approximately 420-800 ms after stimulus presentation. This negativity is evident primarily in the left fronto-temporal regions and is more pronounced for words rated high in BOI.

To examine the effects of grounded semantic richness in the production of these four ERP components, difference waves were calculated by subtracting the value of the averaged low BOI ERP from the averaged high BOI ERP at each 4 ms time point. Then, as described above, 99% Bayesian credible intervals were calculated and plotted at each time point. If these intervals extend past, and include zero, then it can be concluded that a model allowing for the difference between conditions to be not-zero at that time point is not compellingly stronger than a model representing the null hypothesis. For those time points where zero is not included within the credible intervals, it can be concluded that a model describing a non-zero difference better predicts the observed data than does a model reflecting a null hypothesis. Full interpretation of these difference waves and credible intervals requires an examination of the timing and direction of the non-zero differences within the context of the original averaged ERPs. Only electrodes in which notable differences were observed will be presented here.

Figure 6 shows the difference wave for electrode 8 (close to the midline, right hemisphere, parietal region). Approximately 300 ms after stimulus presentation, there is a brief instance where the non-zero model appears more probable than the null hypothesis. However, given that the difference wave is reliably negative at this time, this non-zero effect may be indicative of meaningful condition differences, especially given the conservative thresholds used in these analyses. This difference reflects either the N400 or the early portions of the pronounced P600 evident in Figure 14 (see Electrode 8). As the N400 is sensitive to semantically incongruent information, and High BOI words are thought to be more congruent with imageability, this information is suggestive that these differences are due to increased positivity during the early moments of the P600, reflecting the participants' reanalysis of low BOI words because lower levels of motor knowledge led to more extensive decision-making processing regarding whether a word is easily imageable.

Experiment 3. The same four ERP components are evident in this experiment as are in Experiment 2. ERP waveforms for individual electrodes are presented in Figure 17 while Figure 18 depicts a full scalp time course of ERP polarity. The P200 is evident in all but the central-frontal electrodes and is more pronounced in the left hemisphere. The N400 is seen in all but the central-parietal regions and is most pronounced in the fronto-temporal regions. For words rated low in EE, the N400 is more pronounced in the right hemisphere, whereas it is more pronounced in the left hemisphere for words rated high in EE. The N600 is most evident for words rated high in EE and is most pronounced in frontal regions of the left hemisphere. Through visual inspection, it appears that the left-frontal negativity is more extreme than was observed in Experiment 2. The P600 is more positive and persists longer for words rated low in EE. Visual inspection suggests that this positivity is less extreme than was observed in Experiment 2.

As in Experiment 2, difference waves were calculated by subtracting the averaged ERP for words rated low in EE from the averaged ERP for words rated high in EE every 4 ms after stimulus presentation, and these figures can be interpreted as described above in Experiment 2 (Figures 19-29). Only those difference waves that illustrate non-zero differences are presented.

Negative differences in the P200 are evident in Figures 19-21 (electrodes 1, 3, 5; left hemisphere, frontal and parietal regions) suggesting that low EE abstract nouns required greater amounts of processing at this stage. It appears that there is no P200 evident for words rated high in EE in frontal regions (Figure 17; electrodes 1, 2, 3; 1 & 3 left hemisphere), suggesting that words rated high in EE required very little initial processing in this SCT given their congruence with the decision criterion. However, it is also possible that this difference reflects an early onset of the N400 for these trials, though this may suggest that high EE abstract nouns require more effort to integrate contextually or that early processing at this time reflects the processing of emotion information itself. Words rated high in EE consistently produced more negative deflections between 200 and 800 ms after stimulus presentation. While the later windows appear to be trending positive and can be interpreted as low EE words producing a greater P600 reflecting additional processing due to task incongruence, the 200-400 ms window is less easily interpreted. These data suggest that high EE words, which are hypothesized to be the most typical exemplars of abstract concepts in this experiment, may be either more difficult to process contextually, or are more difficult to retrieve from long term memory, despite task demands priming abstractness.

Bilateral positive P200 condition differences are evident, suggesting greater early processing of words rated high in EE (Figures 24-28; electrodes 14, 16, and 24-26 respectively; see Figure 13 for spatial references). These differences occur predominantly in the right hemisphere and encompass primarily temporal and occipital regions with some parietal and inferior temporal lobe effects evident. As a result, for these electrodes, it can be concluded that a model that accounts for the effects of EE is a better predictor of these data than is a model representing a null hypothesis without this effect. Unlike Experiment 2, these P200 differences cannot be interpreted as additional processing of atypical task exemplars. However, as per Wang et al. (2019), these P200 differences may reflect increased processing of emotion information itself.

Evidence for the superiority of a model including the effects of EE in the N400 deflection is apparent in left hemisphere fronto-parietal regions, and in the right fronto-parietal (Figures 19-22; electrodes 1, 3, 5, and 11 respectively; see Figure 13 for spatial references) ranging from 290 to 450 ms after stimulus presentation. In the left hemisphere, a negative deflection occurs during this time, illustrating that the N400 was more pronounced for words rated high in EE. Consequently, these data reveal increased activity during this window for emotion information itself as it cannot be reasonably concluded that high EE abstract concepts are more difficult to retrieve or to contextualize in Experiment 3, especially when the behavioural data show that these words were responded to more quickly and accurately. Unlike the electrodes that showed increased P200 activity for high-EE words, the electrodes showing increased processing for high-EE words during the N400 are located on the left hemisphere, predominantly located over frontal and parietal regions. These data may have been produced in part by more extreme negativity during a N170, which has been found to be influenced by emotion information (Zhang et al., 2014).

Condition differences are evident at several left-hemisphere electrodes between 500-800 ms after stimulus presentation (Figures 19, 21, 22, and 29; electrodes 1, 5, 11, 13, and 29). In the left fronto-temporal regions, positive differences occur late in the ERP and may reflect an N800, which suggests greater amounts of activity for words with more emotion information, which is characteristic of this deflection (De Pascalis et al., 1996). Negative differences between 500 and 750 ms after stimulus presentation in the temporal lobe (Figure 13) occurs during a P600 window with words rated low in EE showing greater positive deflections, capturing extended effort for processing atypical abstract nouns. However, the positive deflection at this time quickly returns to baseline, where the later negative differences appear at 500 and 750 ms after stimulus presentation. It is possible that this reflects both a P600 and a N600/800 in the left temporal lobe that are counteracting one another as their signals are summed. If this is true, then the later component of the ERPs should be viewed as competing signals reflecting additional attention to low-EE nouns due to task incongruence being expressed simultaneously with increased emotion processing for the high-EE abstract nouns. Electrode 29 also shows a P600 component with words rated low in EE having a more pronounced deflection occurring in the anterior fronto-temporal area (Figure 29; electrode 29), further suggesting additional processing of low-EE abstract concepts.

Experiment 4. The same four ERP components are evident in Experiment 4 as observed in Experiments 2 and 3 (Figure 30). A full-scalp topographic time course of ERP activity is depicted in Figure 31.

The P200 component is evident bilaterally in temporal and occipital regions, though visual inspection suggests the P200 is less pronounced than in Experiment 3. This result likely reflects the comparative ease of this task compared to that of Experiment 3 (i.e., concrete nouns are generally responded to more quickly and accurately than are abstract nouns; Newcombe et al., 2012). The N400 is also evident bilaterally in all electrodes except for the most central electrodes. The N400 is most pronounced in left frontal-temporal areas. The P600 appears in left frontal regions and visual inspection shows the N600 to be more negative than in Experiments 2 and 3 and is most evident in temporal, parietal, and occipital regions with visual inspection revealing greater magnitude in the right hemisphere.

As in Experiment 3, difference waves calculated by subtracting the averaged ERP for concrete nouns rated low in EE from the averaged ERP for those rated high in EE and can be interpreted as in Experiments 2 and 3 (Figures 32-35; electrodes 3, 5, 11, and 29 respectively). Only those difference waves that illustrate non-zero differences are presented.

All meaningful differences were observed in frontal and temporal regions in the left hemisphere. A negative difference between 150 and 200 ms after stimulus presentation was recorded in electrode 3 (Figure 32). At this location, there was no marked P200 component for words rated high in EE, whereas the ERP for words rated low in EE shows a small positive deflection. The difference in the P200 between these conditions could imply that low-EE concrete nouns require additional processing. However, this interpretation does not seem plausible given that low-EE concrete nouns are typical exemplars of concrete concepts.

Alternatively, this difference could be interpreted as an early onset of the N400 for both conditions, but more so for concrete nouns rated high in EE. This alternative would be interpreted as additional processing to integrate high levels of emotion information with the SCT decision criterion in this experiment because emotion information is indicative of abstract concepts, thereby making concrete nouns rated high in EE diagnostically incongruent with the decision criteria to respond concrete nouns.

A negative difference between 300 and 450 ms after stimulus presentation is evident in electrodes 3 and 5 (superior fronto-parietal, left hemisphere; Figures 32 and 33). It appears that the N400 at this time is reflecting additional processing for high-EE concrete concepts. However, in Experiment 3, the same pattern was observed for abstract words rated high in EE. The greater negativity to both concrete and abstract nouns rated high in EE may suggest that the greater N400 in this experiment reflects the processing of emotion information and/or the additional effort to integrate high levels of EE within the context of this experiment's decision criterion. Concrete nouns rated high in EE produced a more negative deflection across the entire ERP time course at electrodes 3 and 5 (Figures 32 and 33). However, there are no truly pronounced ERP components evident at these locations (Figure 30). This comparatively flat ERP suggests that, at these locations, the total activation of the surrounding areas may have summed to a predominantly null ERP. Although this makes the interpretation of these data more difficult, the reliably more pronounced negativity for concrete concepts rated high in EE is in line with the observations in Experiment 3 that high EE nouns require additional processing due to their grounded semantic richness obtained through emotion experiences.

Lastly, late (600-800 ms after stimulus presentation) negative differences are evident in electrodes 11 and 29 (inferior fronto-temporal regions; Figures 34 and 35). The ERP component at this time for electrode 11 (Figure 34) is relatively flat for words rated low in EE but appears to reflect a N600 for concrete nouns rated high in EE, again showing additional processing for either stimuli with greater levels of grounded semantic richness that are incongruent with current task demands or for emotion information itself.

Discussion

Collectively, the data presented above largely support the initial behavioural and ERP hypotheses. Behaviourally, response latencies were hypothesized to be faster to stimuli with greater amounts of grounded semantic richness when that grounded semantic richness is congruent with task demands (Experiments 2 and 3) and to be slower when that grounded semantic richness is incongruent with task demands (Experiment 4). An extended discussion of these data's implications for the grounding of conceptual knowledge is detailed in Chapter 3. To summarize: grounded information is automatically activated as part of a simulation during the processing of conceptual knowledge regardless of whether that knowledge is task relevant or beneficial to successful task completion.

Greater amplitudes during the P200, N400, and P600 windows were predicted for words rated low in BOI and EE in Experiments 2 and 3 due to the additional processing required for stimuli with less diagnostic grounded semantic richness, while greater amplitudes to words rated high in EE were predicted during the same windows in Experiment 4 due to the incongruence between grounded semantic richness and the decision criterion.

The evidence suggests that, when accessing conceptual knowledge, grounded semantic richness information that was obtained through bodily and emotion experiences with the environment is automatically activated or simulated. Further, the ERP data suggest that grounded semantic richness effects are not singular in nature. Rather, ERP components reflecting the influence of grounded semantic richness are produced from several neural processes, in both hemispheres, and come online at varying times after stimulus presentation, as evidenced by condition differences across four ERP components. This supports the *soft assembly* perspective of conceptual knowledge (Anderson et al., 2013). Anderson et al. (2013) propose that cognitive processes are unlikely to occur in discrete brain regions; it is more likely that cognitive processes are "softly assembled" across several brain regions at once. Softly assembled objects are only identifiable as discrete entities at a specific moment in time. However, there is never a particular number or configuration of constituents that defines the object. For example, a flock of birds is softly assembled; a flock can be recognized as such, but there is no distinct number or configuration of birds that qualifies the birds as a flock. Similarly, cognitive processes like memory, attention, or language comprehension are likely performed across several brain regions concurrently, with no discrete combination of activity distinctly qualifying the activation as a particular process. Any observable neural response to a stimulus will, as a result, be observed as a shift within an ever-changing dynamic system rather than a discretely observable event. Data, such as those presented here, would not be observed if conceptual knowledge was stored together as a discrete abstract representational code (Niedenthal et al., 2005). These data contribute to the growing body of work that is demonstrating *how* cognitive processes occur the way they do.

Electroencephalography Results.

An understanding of the ERP data is important because they provide a time course analysis that complements the interpretations provided by an analysis of response latencies and accuracy (Kounios & Holcomb, 1994). Although a substantial amount of EEG data was discarded due to the presence of artifacts, one can be confident in the data because the ERP components observed in the experiments described above are consistent with what is expected in SCT experiments. There were four primary ERP components evident for all three experiments. The first, the P200, has previously been observed in anterior and central regions, and greater magnitudes have been interpreted as reflecting task difficulty and automatic evaluation of stimuli (e.g., Taylor & Khan, 2000), as well as semantic richness effects (Kounios et al., 2009). Second, the N400 has been observed most frequently in central and parietal regions and has been interpreted, in part, as reflecting the amount of effort needed to integrate stimuli into current task demands (e.g., Heinze et al., 1998). Third, the P600 has been observed in centro-parietal regions and is thought to reflect automatic reanalysis of stimuli. Finally, the N600 has been observed over fronto-central regions and has been interpreted as reflecting additional processing due to perceived incongruities (e.g., Du et al., 2013). Each component will be discussed in turn below.

P200 Observations. In the first 300 ms after stimulus presentation, visual inspection of scalp topography (Figures 15, 18) shows that, in Experiments 2 and 3, early positivity is most evident and diffuse to words rated low in grounded semantic richness, regardless of its type (BOI or EE), and its congruence with decision criteria. In Experiment 4 (Figure 39), however, the same pattern is observed for words rated high in EE. These observations support the hypothesis that greater P200 amplitudes would be produced by stimuli with comparatively low levels of task-congruent grounded semantic richness.

Interestingly, visual inspection suggests that the scalp topography of the early positivity differs between experiments. In Experiment 2, when the primary source of grounded semantic richness was BOI, early positivity was predominantly posterior for low BOI trials. In Experiments 3 and 4, however, when the source of grounded semantic richness was EE, early positivity is more frontal and more focused in the left hemisphere. These data are similar to those of Pauligk et al. (2019) who reported more pronounced central and posterior concreteness effects, whereas emotion effects were observed more frontally and in the left hemisphere. This difference in ERP distribution also supports the hypothesis that, from a grounded cognition perspective, qualitatively different ERP scalp distributions should be observed as a function of the nature of a word's grounded semantic richness.

Kounios et al. (2009) observed that the P200 increased in magnitude for semantically rich trials (as observed in Experiment 4), but Kounios's (2009) interpretation does not easily align with the current data. Kounios et al. proposed that semantically rich trials produce higher P200 magnitudes; however, more difficult trials are thought to also produce higher P200 magnitudes. Given the widely observed effects of semantic richness correlating with faster response latencies, these two interpretations are not compatible. In other words, as in Experiments 2 and 3, SCT trials with stimuli rated high in task-congruent grounded semantic richness would be considered relatively easy, and subsequently predicted to have both a more pronounced P200, due to greater levels of grounded semantic richness, and a lower P200 due to the comparative ease of processing. In Experiment 4, however, one might predict that the increased amounts of emotion information for concrete nouns would make the decision, "Is this a concrete noun?" more difficult due to the incongruity between increased levels of EE and the decision criterion of "is the word concrete?", thereby producing longer response latencies and greater P200 magnitudes. The P200 deflections to stimuli rated high in EE in Experiment 4 would also be predicted to be greater in amplitude due to the comparatively greater levels of grounded semantic richness. Although the response latencies were longer for High EE trials, the P200 in Experiment 4 was of lower magnitude for words than in Experiments 2 and 3. More research is needed to confirm whether the P200 deflection reflects activity from multiple locations (reflecting multiple streams of automatic processing), thus producing dissociable effects that can be produced independently by either grounded semantic richness, task relevance, or trial difficulty.

Interestingly, in Experiment 2, the effects of BOI during the P200 were statistically evident in the right hemisphere at a parietal electrode, whereas in Experiment 3, EE effects in the P200 were observed in the left hemisphere in frontal and parietal electrodes, and in Experiment 4, the effect of EE on the P200 was also evident in the left hemisphere, at a frontal electrode. These differences are perhaps due to the source of the grounded semantic richness in the experiments; BOI and EE are processed differently very quickly after stimulus presentation. In Experiment 3, when the influence of EE was congruent with task demands, EE improved the strength of a predictive model at frontal sites bilaterally. Specifically, abstract nouns rated low in EE elicited lower P200 amplitudes at these electrodes, which suggests that words with less grounded semantic richness did not require as much processing at this stage. As such, it is possible that the increased P200 amplitudes at frontal sites for words rated high in EE may reflect the processing of emotion information itself rather than of task difficulty.

A caveat here is that the P200 component, despite showing condition differences, occurs at the same time across experiments and conditions. This consistent timing across experiments and conditions suggests that the processing differences at this time do not directly reflect or produce the observed response latency differences. Rather, processing differences, as captured in P200 differences in the current experiments, likely influence response times through feed-forward facilitation of later ERP processes. Given the absence of a visible P200 for high EE trials in Experiment 4, it could be concluded that the type of processing that this component captures does not reflect task difficulty incurred by task relevance per se. Rather, it appears as though what is being observed in the current experiments, in addition to the reported P200 effects of additional processing for atypical task exemplars, is evidence of very early, automatic processing of grounded semantic richness itself. Further, the fact that the dimensions of grounded semantic richness that were manipulated in these experiments were grounded in bodily experience lends credibility to the claim that conceptual knowledge is inherently grounded in sensory, motor, and emotion experiences.

Across all experiments, whenever grounded semantic richness was high, regardless of congruence with task demands, diminished P200 components were observed in frontal regions, though there were some hemispheric differences concerning the specific electrodes that showed the effects. However, when the source of grounded semantic richness was EE, and that information was task congruent, greater P200 amplitudes were observed in more posterior electrodes, primarily in the right hemisphere. When high levels of EE were incongruent with task demands, these effects were not seen, though the P200 was still diminished in frontal sites for high-EE trials.

In summary, the P200 reported here does not appear to be a singular component that solely captures task difficulty. A visual comparison among experiments suggests that the P200 is more pronounced for concrete than for abstract nouns, and yet further pronounced on trials that contextually require deeper processing. Furthermore, when the source of grounded semantic richness is BOI, condition differences are observed in the right hemisphere; yet differences are observed primarily in the left hemisphere when EE is the critical source of grounded semantic richness, with these differences more evident when EE is task-relevant in facilitating responding to abstract nouns. These data suggest that the activation of grounded semantic units is inherent to conceptual processing in single word presentation, but that the extent to which that information is processed varies as a function of task congruence.

N400 Observations. The topographical plots (Figures 14, 18, and 30) for all three experiments highlight some differences in the negative activity occurring 200-500 ms after stimulus presentation, which may be best interpreted as a N400 component. The earliest negative deflections are evident in Experiments 3 and 4 in both high- and low-EE conditions, and primarily appear in left posterior regions. This early posterior negativity is less evident in Experiment 4 (responding to concrete nouns) than in Experiment 3 (responding to abstract nouns). Although stimuli in both experiments varied along the EE dimension, EE was not diagnostic of a go-trial in Experiment 4, and thus did not exert facilitatory response latency effects. However, the early N400 components between 200 and 300 ms after stimulus presentation appear more negative to low-EE trials in both experiments. As such, this early N400 activity could be interpreted as reflecting the automatic processing of EE, regardless of task relevance, with greater negativity when EE was diagnostic of a go-trial, and additionally reflective that more processing was required, across experiments when EE information is less available, regardless of task relevance. In Experiment 2, however, where participants were responding to concrete nouns and BOI was the manipulated dimension of grounded semantic richness, left posterior N400 activity is also evident, though not pronounced until approximately 300-400 ms after stimulus presentation (Figure 18), and is most pronounced on High BOI (task congruent) trials. These data collectively suggest that semantic information obtained through emotion experiences is processed automatically between 200 and 400 ms after stimulus presentation, whereas semantic information obtained through physical interactions with the environment is processed between 300 and 400 ms after stimulus presentation in the same posterior brain regions. As such, there is no single interpretation of the left posterior N400 across these experiments, supporting the assertion made above that this component is not a single entity, as neither the nature of grounded semantic richness being processed nor the relevance of high levels of grounded semantic richness are sufficient alone to predict the timing or magnitude of the N400.

Although visual inspection of the N400 in Experiment 2 suggests increased intensity for High BOI trials, analysis of the difference waves show no evidence of condition differences during the N400 window. This result was unexpected given the common interpretations that the N400 captures contextual integration or memory retrieval. Further, the result is especially unexpected given the marked response latency differences observed in Experiment 2, and that concrete nouns have been found to produce more pronounced N400s than do abstract nouns (Holcomb et al., 1999; Kounios & Holcomb, 1994). One possible explanation of this observation is that all Experiment 2 stimuli were comparably easy to contextualize as imageable given the extended intertrial interval, the relative simplicity of the task, and that all go-trials were concrete nouns. As a result, although an N400 is evident in Experiment 2, these data do not support the conclusion that BOI is differentially processed during this time.

Clearly, the observed N400 does not reflect the same semantic processes in all three experiments. N400 activity was observed in all three experiments, but meaningful condition differences were only observed during the N400 window in Experiments 3 and 4 when EE was the manipulated dimension of grounded semantic richness. It can be concluded, then, that the negative ERP activity during the N400 window in these three experiments reflects heterogeneous semantic processes, and that this activity is particularly sensitive to grounded semantic richness obtained from bodily emotion experiences. Future research should look at components before and after the N400 when looking for ERP evidence of grounded conceptual processing of other grounded semantic richness dimensions.

It is interesting that there were condition differences in Experiment 4 during the N400 window. Even though emotion information did not strictly need to be processed to successfully recognize a concrete noun, it is important to remember that the no-go trials were abstract nouns. If, as hypothesized, abstract concepts are intrinsically represented through their emotion information, it is possible that participants responding under an "Is this a concrete noun" decision criterion may have automatically activated EE information so as to recognize a no-go trial. That is, when emotion information is even implicitly relevant, N400 magnitudes automatically reflect the amount of emotion information on that trial. If participants were inhibiting their responses when high levels of EE were activated (i.e., if the trial initially led toward a decision that the stimulus was an abstract noun), one would predict the response latency differences that were observed (high-EE concrete nouns being initially recognized as abstract concepts, thereby requiring inhibition), and the observed N400 condition differences even though EE was not diagnostic of a go trial. This sort of interpretation is congruent with previous research that has suggested that the N400 can capture the inhibition of automatically activated incompatible knowledge (e.g., Debruille, 1998; Kounios, 1996).

The topographical plots for all three experiments (Figures 15, 18, & 31) are consistent with prior research demonstrating that the scalp distributions of the N400 to abstract and concrete nouns are known to differ, suggesting that the cognitive and neural demands for processing both word types are fundamentally different (Holcomb et al., 1999; Kounios & Holcomb, 1994; West & Holcomb, 2000). Such differences have been interpreted as being the product of at least two separate neural contributors to the N400 including an imagine system and a verbal processing centre (Kounios & Holcomb, 1994). Holcomb et al. (1999) showed that concrete nouns are more likely than abstract nouns to produce an N400 in frontal regions. This observation is incongruent with the current findings. However, given the go/no-go design employed in Experiments 2-4, there can be no direct comparison made between the experiments presented here and Holcomb et al.'s (1999) experiments as data for responses to concrete and abstract nouns are not available under the same task demands in the experiments presented here. That is, in the current go/no-go design, data are only available for concrete or abstract trials in any one experiment, whereas in a yes-no design, data are available for both trial types in the same experiment with the same decision criteria. However, these data still support a modal perspective of conceptual knowledge processing in that amodal theories would not intuitively predict separate neural contributors for the processing of different dimensions of grounded semantic richness.

In Experiment 2, the only statistical evidence of a N400 ERP condition difference was observed in the frontal region of the right hemisphere, with words rated high in BOI producing a more negative ERP beginning as early as 300 ms after stimulus presentation. This is in line with previous research, described above, suggesting that concrete nouns should activate a frontal imagine system, and that the most imageable words produced the strongest effect in these regions (Holcomb et al., 1999). In Experiments 3 and 4, however, statistical evidence of N400 differences was found almost exclusively in frontal and medial regions of the left hemisphere. In all such cases, the N400 was most pronounced for words rated high in EE, regardless of whether participants were responding to abstract or concrete nouns. The only exception to this was a statistical difference showing more pronounced N400 negativity for words rated low in EE in the right hemisphere in Experiment 3. It is possible that this difference reflects, for atypical abstract nouns, a unique processing difference that occurs in the right hemisphere, whereas grounded semantic richness derived from EE is processed predominantly in the left hemisphere. These data support the grounded cognition hypothesis that emotional experiences with words' referents should be automatically activated whilst being neurologically discernible in semantically influenced ERP components.

Late ERP Observations. Late ERP differences were observed in all three experiments. N600 condition differences were observed in the left hemisphere in both Experiments 3 and 4, with more pronounced negativity observed for high-EE trials. Due to the different decision criteria in each experiment, this additional negativity can be interpreted as additional processing of emotion information, regardless of its task relevance. Given how late in processing these effects were observed, it is unlikely that these differences are directly contributing to response latencies. This interpretation is supported by the differences in response latencies for high-EE trials in each experiment, with high-EE words being responded to more quickly in Experiment 3, but more slowly in Experiment 4. Therefore, what was observed in the N600 in Experiments 3 and 4 would be best explained as sustained elaborative processing of emotion information itself independent of task demands. The production of additional neural activity by emotion information, regardless of its facilitatory or inhibitory contribution to response execution, suggests that it is an automatic element of conceptual processing when grounded semantic richness obtained from bodily emotion experiences is available.

Late positive condition differences were observed in the P600/LPC in Experiment 2 and 3 with less semantically rich trials producing greater positivity. That these differences were observed in low grounded semantic richness trials is congruent with the interpretation that the P600 captures the amount of effort needed to process a concept and is reflective of trials that require further processing (Hagoort, 2003). The right hemisphere difference for Experiment 2 was found over the superior parietal area, whereas the left hemisphere difference for Experiment 3 was found in inferior temporal regions. These results suggest that, although P600 differences are being evoked in both experiments by trials that are incongruent with task criteria due to having less grounded semantic richness, the neural generators responsible for the additional processing required for these experiments is different due to the specific type of grounded semantic information (BOI and EE) being processed. Similar to the P200 and N400 discussions above, these data suggest that, much like how semantic richness is not derived from a single source of information, the P600 component is not a singular event with a single underlying process (e.g., Kounios et al., 2009).

Visual inspection of the topographic plots for Experiments 2, 3, and 4 (Figures 15, 18, and 31) shows that more pronounced negativity was observed in the left hemisphere's frontal and temporal regions for words rated high in EE in Experiments 3 and 4. That this result was not observed in Experiment 2 suggests that this observation is unique to EE and not indicative of grounded semantic richness in general, but supports the observation that different sources of grounded semantic richness account for unique variance in SCT and LDT performance (Pexman et al., 2008). Again, regardless of task relevance and the associated behavioural consequences, evidence of grounded semantic richness is observable with ERP analyses.

Conclusions. The use of EEG to monitor SCT performance shows that ERP waveforms capture condition differences elicited by the manipulation of grounded semantic variables. Specifically, in the experiments presented above, the manipulated dimensions of grounded semantic richness did not need to be activated to successfully complete the experimental tasks. That ERP waveforms reflect varying levels of automatically activated grounded semantic richness that is not being explicitly processed by participants is compelling evidence that grounded semantic richness is an automatic and integral part of conceptual knowledge.

The observation that grounded semantic richness obtained through emotion experiences was incongruent with concrete noun recognition in Experiment 4 further supports the interpretation of these data as reflecting the grounded nature of conceptual processing (Vigliocco, et al., 2009). If accessing grounded information was somehow strategic in nature, rather than a necessary and automatic part of conceptual activation, the behavioural and ERP data in Experiment 4 ought not to have demonstrated an influence of emotion information on concrete noun recognition. Rather, given that the task was to identify concrete nouns, participants would have created response decision rules that pertain exclusively to concreteness (e.g., BOI, imageability, etc.), and emotion information, being indicative of abstract concepts, and not concrete concepts, would not influence behaviour or neural activity. As such, these data strongly indicate that grounded semantic information is an integral element in the processing of conceptual knowledge. The addition of EEG measurements helped support these conclusions.

Early processing differences were observed as a function of manipulated grounded semantic richness, suggesting that semantic information is activated within the first 150-200 ms after stimulus presentation. Further, this activation is differentially sensitive to the amounts of grounded semantic information, regardless of task relevance. These observations support the conclusion that modal information is inherently part of conceptual knowledge.

The N400 component was sensitive to the processing of emotion information but was not sensitive to BOI. This observation will be important to researchers choosing the time windows for more typical ANOVA-style analyses and for researchers selecting semantic dimensions for future study. Additionally, the N400 emotion differences in Experiments 3 and 4 varied according to the hemisphere in which they were observed, despite being produced by manipulations of the same semantic dimension (EE). These data help to illustrate when emotion information contributes to response execution in single word presentation SCTs and supports a more full-scalp approach to observing semantic effects, rather than targeting regions of interest, as is more commonly practiced.

Beyond the N400 deflection, care must be taken to dissociate between positive and negative deflections, as they were found, here, to be differentially sensitive to the experimental manipulations. The late positive deflections showed condition differences only in Experiments 2 and 3 and, in both experiments, increased positivity was observed for low grounded semantic richness trials. As mentioned above, this is in line with the interpretation that these trials required additional processing due to their task incongruence. This effect was not observed in Experiment 4, perhaps due to the relatively weaker effects observed when participants were responding to concrete nouns. The Bayes Factors for the behavioural effects in Experiment 4 were an order of magnitude lower than in the other two experiments, despite still providing convincing evidence for statistical models that include EE. Perhaps this indicates that the influence of EE in Experiment 4 was less pronounced than were the manipulated dimensions of grounded semantic richness in the other two experiments. That is, BOI may be integral to concrete nouns even when assessing imageability, and EE may be integral to judging abstractness, while EE may indirectly signal “not concrete” when judging concreteness. This would explain the lower Bayes Factors and the absence of pronounced condition differences in the later positive ERP components in Experiment 4. The N600, however, appears to have been sensitive primarily to the processing of additional emotion information as it only showed condition differences in Experiments 3 and 4. In both experiments, the N600 differences were observed in fronto-temporal regions of the left hemisphere. The similar timing and location support the conclusion that these N600 differences reflect similar neural generators and emotion-information-processing functions.

While some researchers employ jittered stimulus presentation, the experiments presented here did not. Using a variable inter-trial interval is commonly done to avoid the possibility that each stimulus appears at the same phase of a brain wave (e.g., alpha waves). For example, if all go-trials' presentation was phase locked to the peak of the alpha wave, then the data would be systematically biased across all ERP deflections. However, most cognitive experiments employ inter-trial intervals of ~500-3000 ms, whereas the experiments presented here employed at 15,000 ms interval. As such, the probability of such a long interval becoming systematically synchronized with an underlying brain wave was highly unlikely. Additionally, the influence of alpha wave activity is generally removed during filtering. Another reason researchers may employ presentation jittering is to avoid recording anticipatory activity as when participants can reliably predict the presentation of each stimulus. This is important as EEG activity prior to stimulus presentation is frequently used for baseline corrections, and any systematic pattern of activity during that time would thus bias the correction calculation. However, as the delay between stimulus presentations increases, the ability of participants to accurately predict the moment of presentation decreases, thus reducing any predictive activity to random noise in the final analyses.

Collectively, the ERP data presented here suggest that grounded semantic richness effects can be observed early in processing, that grounded emotion effects are evident during the N400 window, and that trials low in grounded semantic richness produce P600 differences when grounded semantic richness is more relevant to task completion. It is exciting to see the effectiveness of full-scalp time course analyses. Though the behavioural effects of grounded semantic richness have been observed for some time, observations of the neural correlates of the differing time course for the activation of semantic knowledge is needed (Amsel, 2011). However, the three experiments reported here represent a first step in testing these hypotheses. That is, to definitively state that the neural regions producing these data are motor and perceptual regions, techniques that allow for greater spatial resolution will need to be employed. Although it is tempting to emphasize the number of ERP condition differences evident in the left hemisphere, where language processes are thought to primarily reside, it needs to be noted that ERP components can be produced by lateralized neural activity, or by contralateral generators whose measurable electrical field is observed in the other hemisphere (Kounios & Holcomb, 1994). Future studies with denser EEG arrays employing techniques designed to increase spatial resolution could clarify the neural regions producing condition differences in ERP analyses (e.g., Current Source Density estimates and Surface Laplacian computation; Burle et al., 2015). Regardless, these data demonstrate that the nature of semantic knowledge activation is performed across the brain in different regions, and that information obtained from bodily experiences with the environment is activated automatically, regardless of task relevance. Conceptual knowledge is, ultimately, grounded in nature.

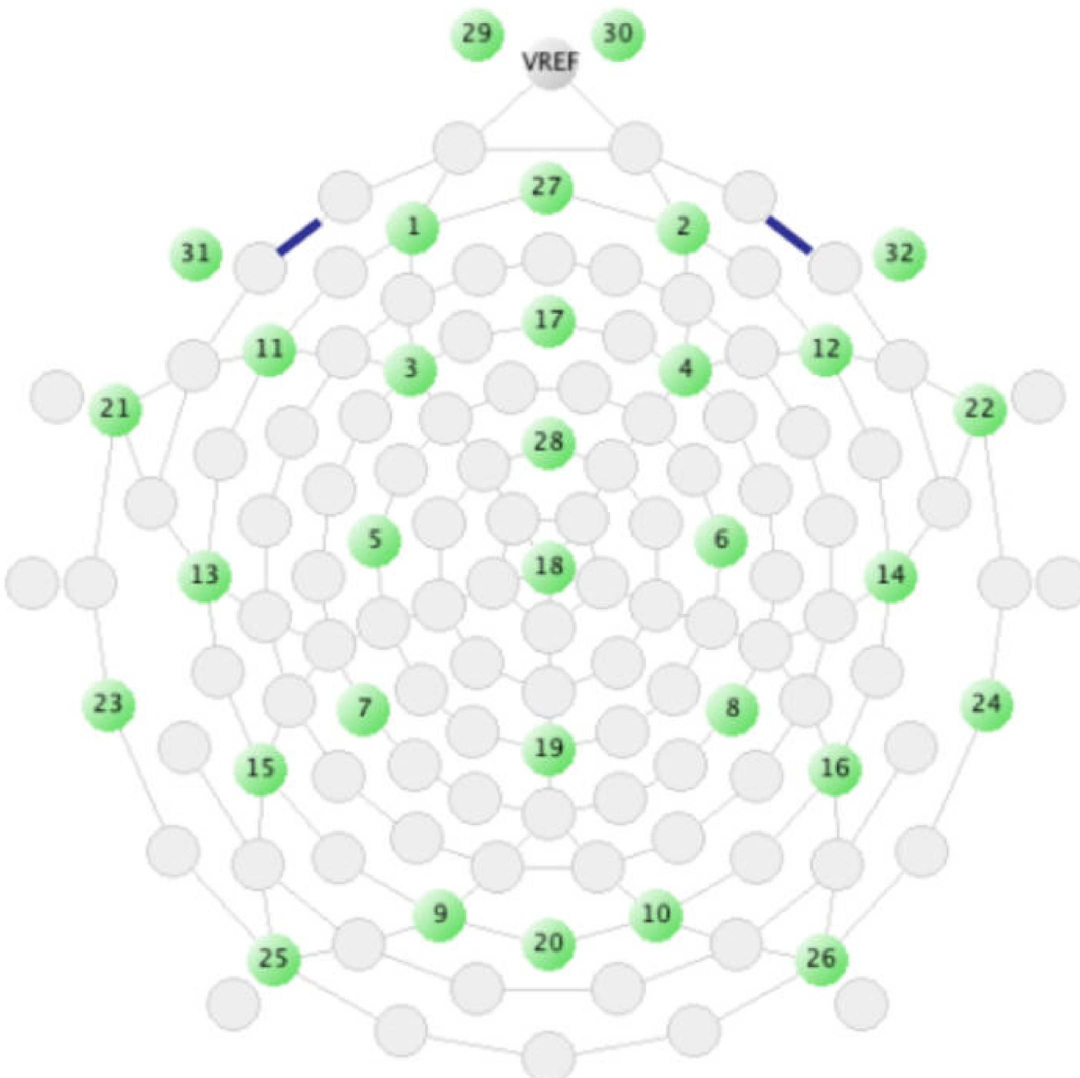

Figure 13. Electrode placement reference for all experiments. View is from above, with a person facing towards the top of the screen. Image obtained from Geodesic Sensor Net Technical Manual (2007).

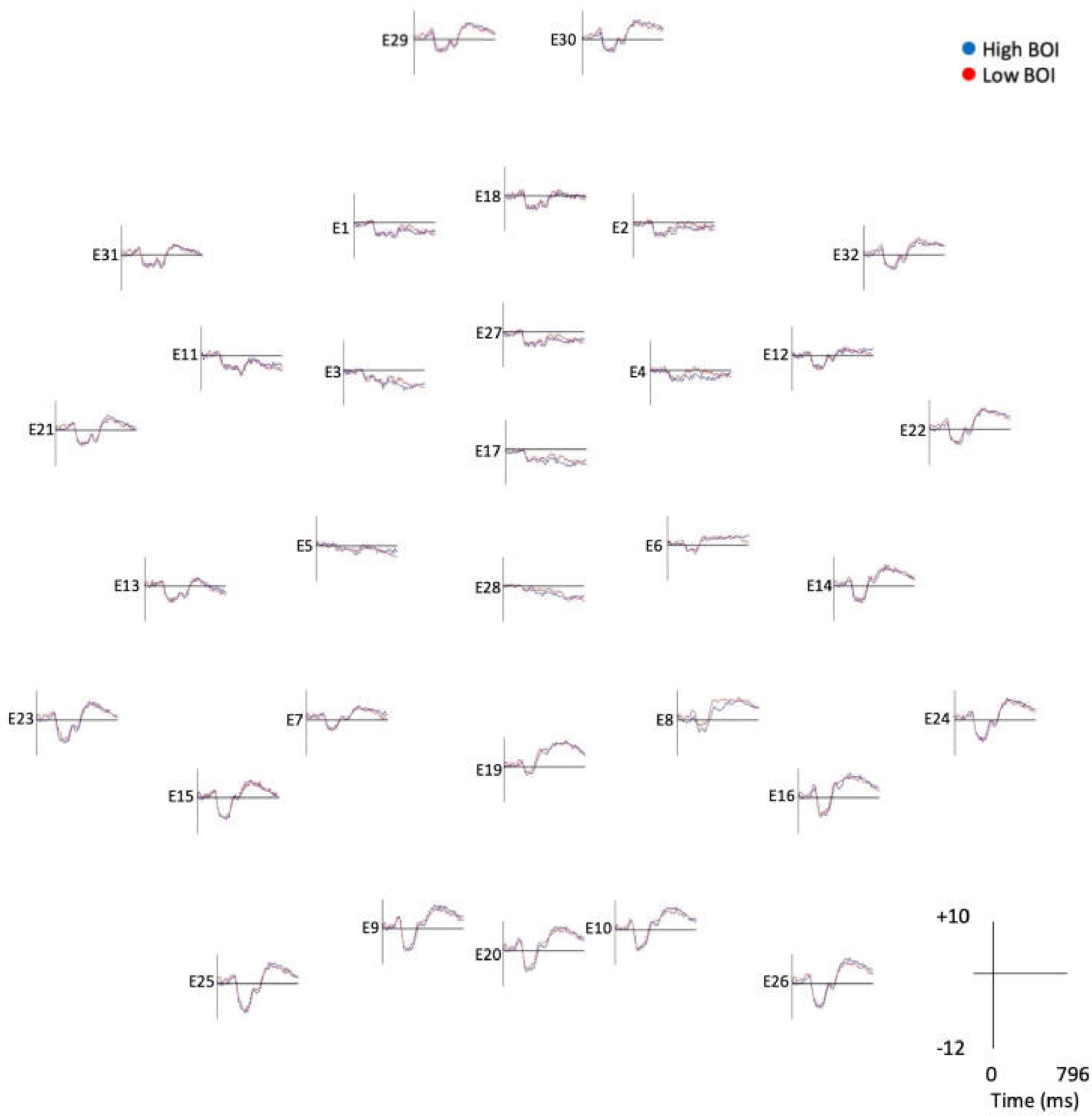

Figure 14. Topographic display of all ERP waveforms for Experiment 2 with all electrodes aligned as per Figure 13.

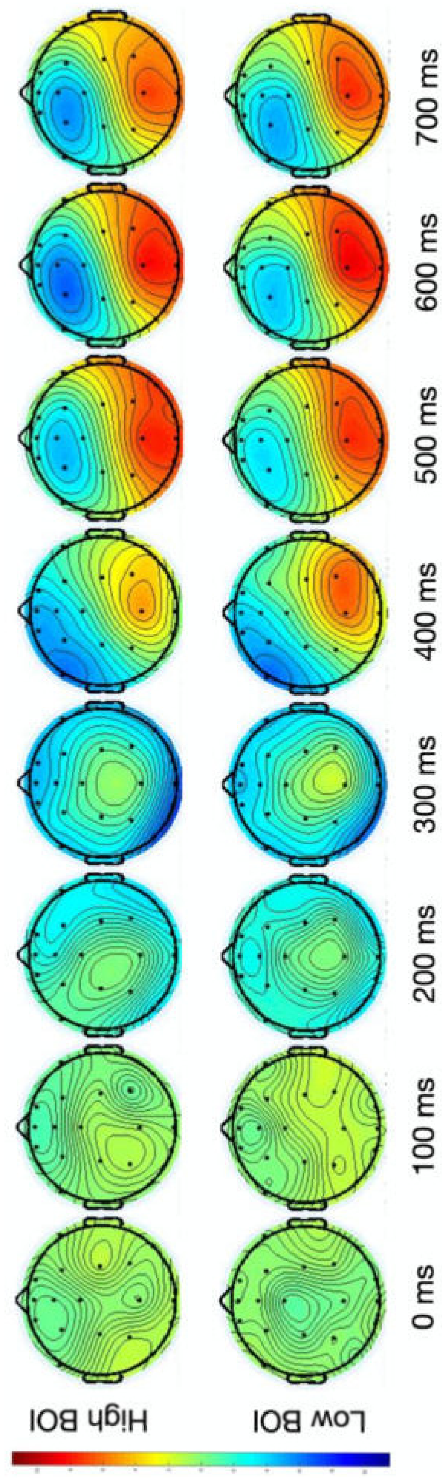

Figure 15. Topographic scalp plot for Experiment 2. Times (ms) are time since stimulus presentation. Red denotes positivity and blue denotes negativity. Scale is -10 to 10 µV.

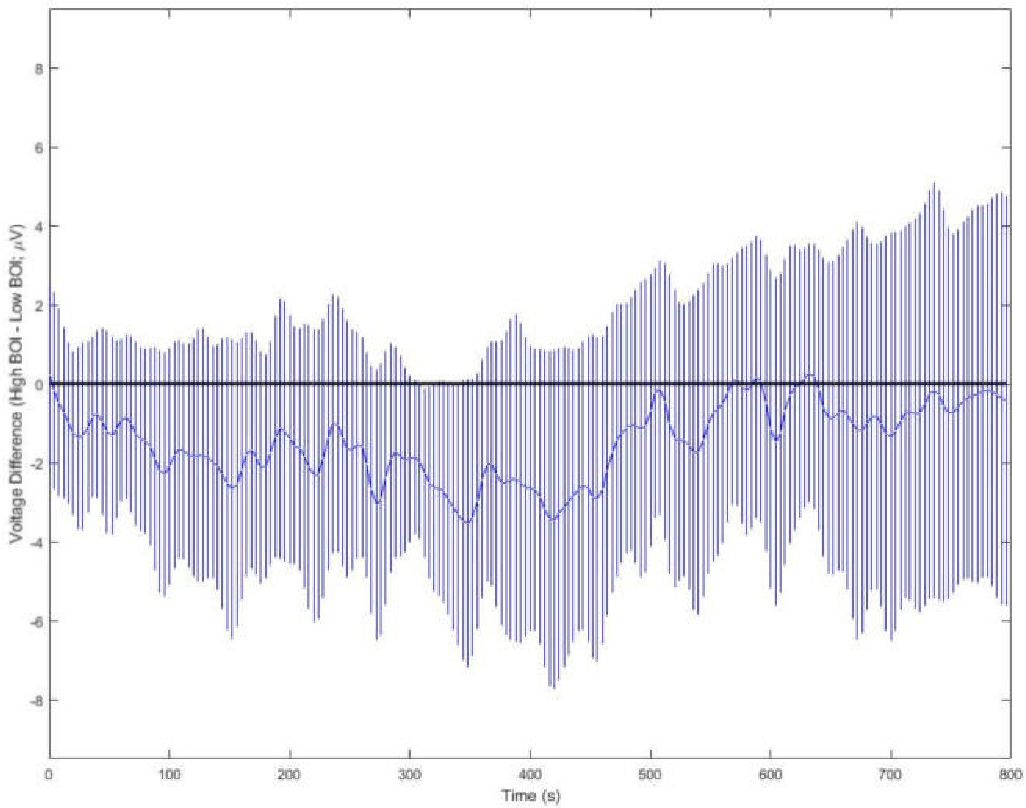

Figure 16. Difference waveform (High BOI – Low BOI) for electrode 8 in Experiment 2. Error bars are 99% Bayesian credible intervals.

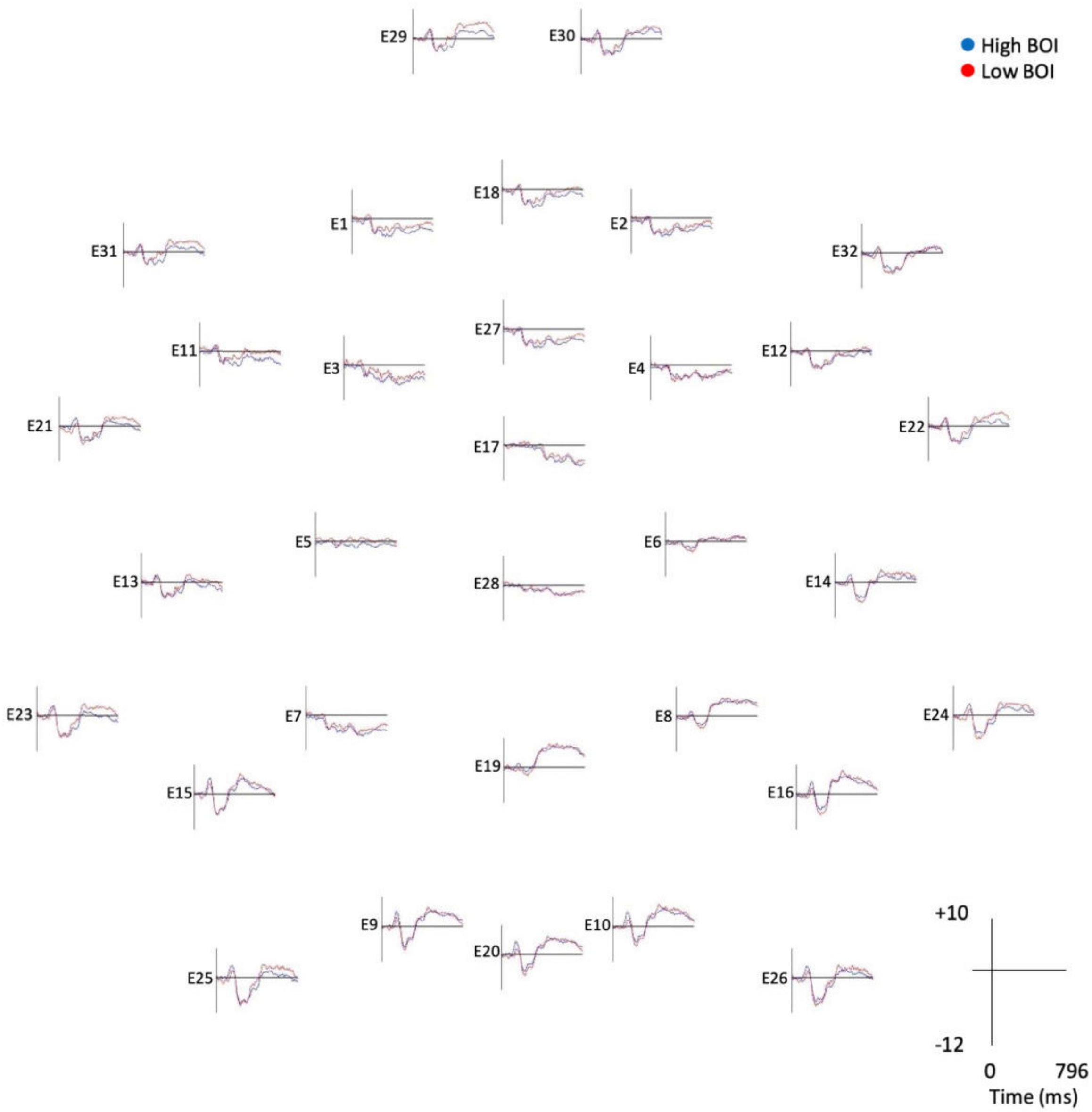

Figure 17. Topographic display of all ERP waveforms for Experiment 3 with all electrodes aligned as per Figure 13.

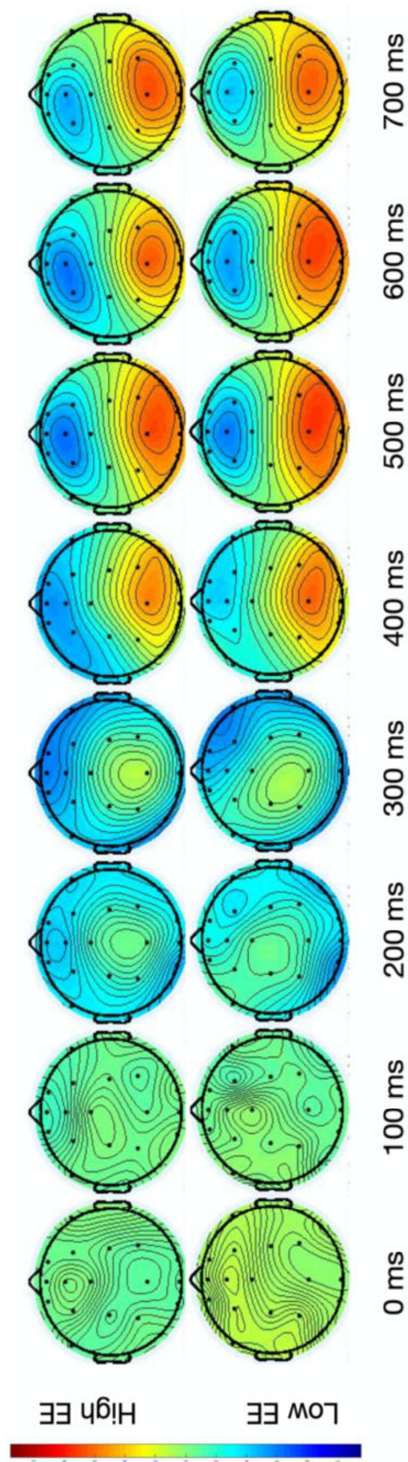

Figure 18. Topographic scalp plot for Experiment 3. Times (ms) are time since stimulus presentation. Red denotes positivity and blue denotes negativity. Scale is -10 to 10 μV.

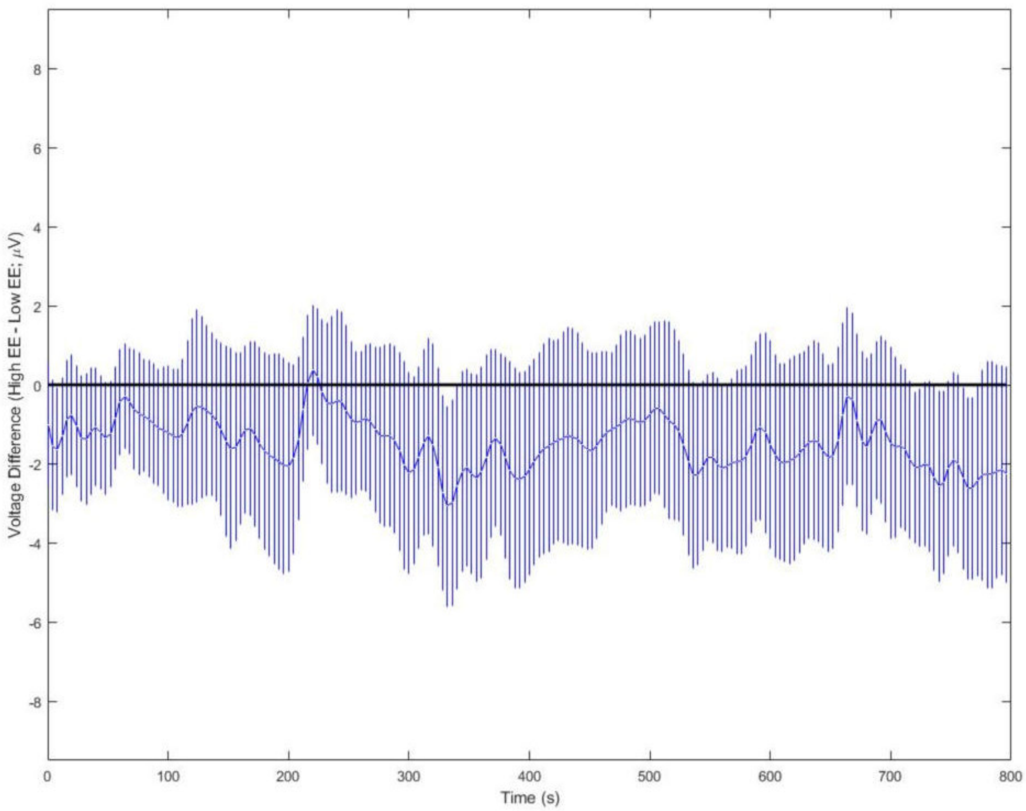

Figure 19. Difference waveform (High EE – Low EE) for electrode 1 in Experiment 3. Error bars are 99% Bayesian credible intervals.

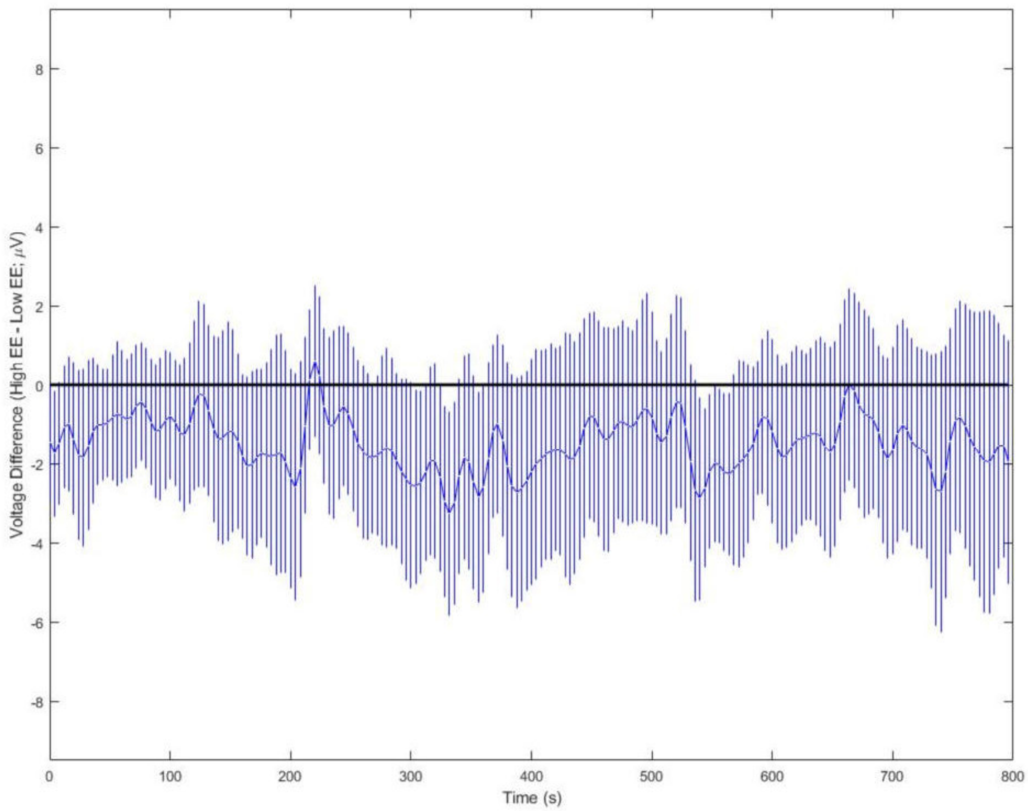

Figure 20. Difference waveform (High EE – Low EE) for electrode 3 in Experiment 3. Error bars are 99% Bayesian credible intervals.

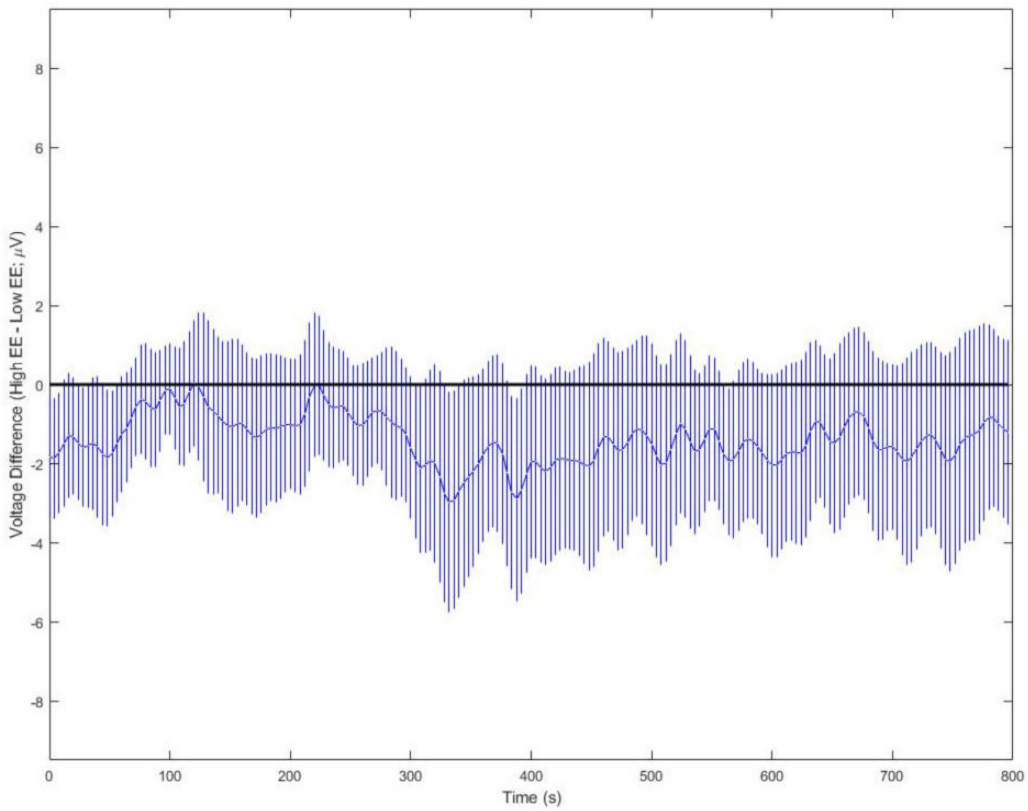

Figure 21. Difference waveform (High EE – Low EE) for electrode 5 in Experiment 3. Error bars are 99% Bayesian credible intervals.

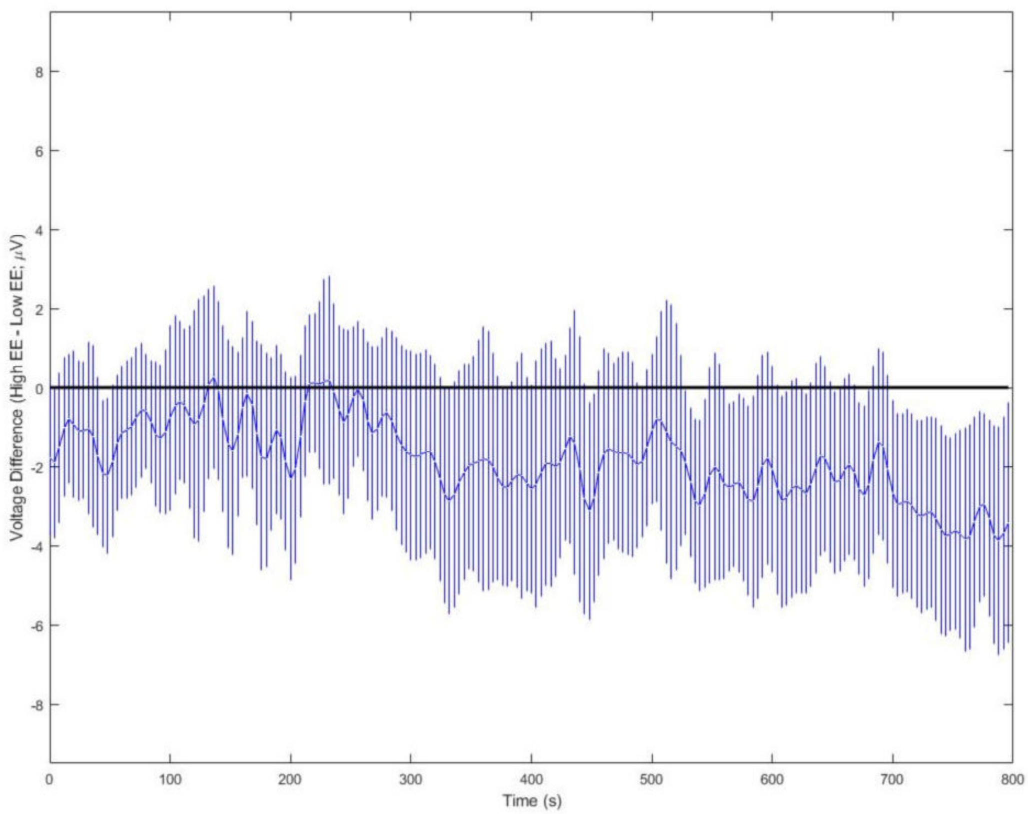

Figure 22. Difference waveform (High EE – Low EE) for electrode 11 in Experiment 3. Error bars are 99% Bayesian credible intervals.

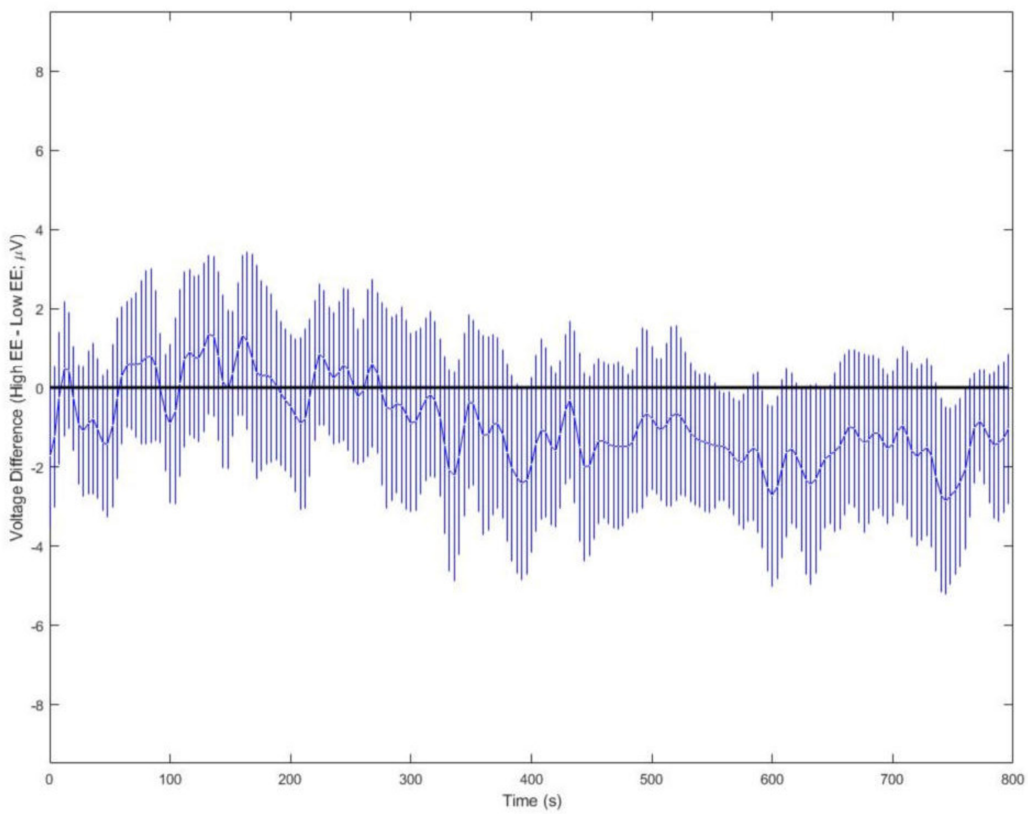

Figure 23. Difference waveform (High EE – Low EE) for electrode 13 in Experiment 3. Error bars are 99% Bayesian credible intervals.

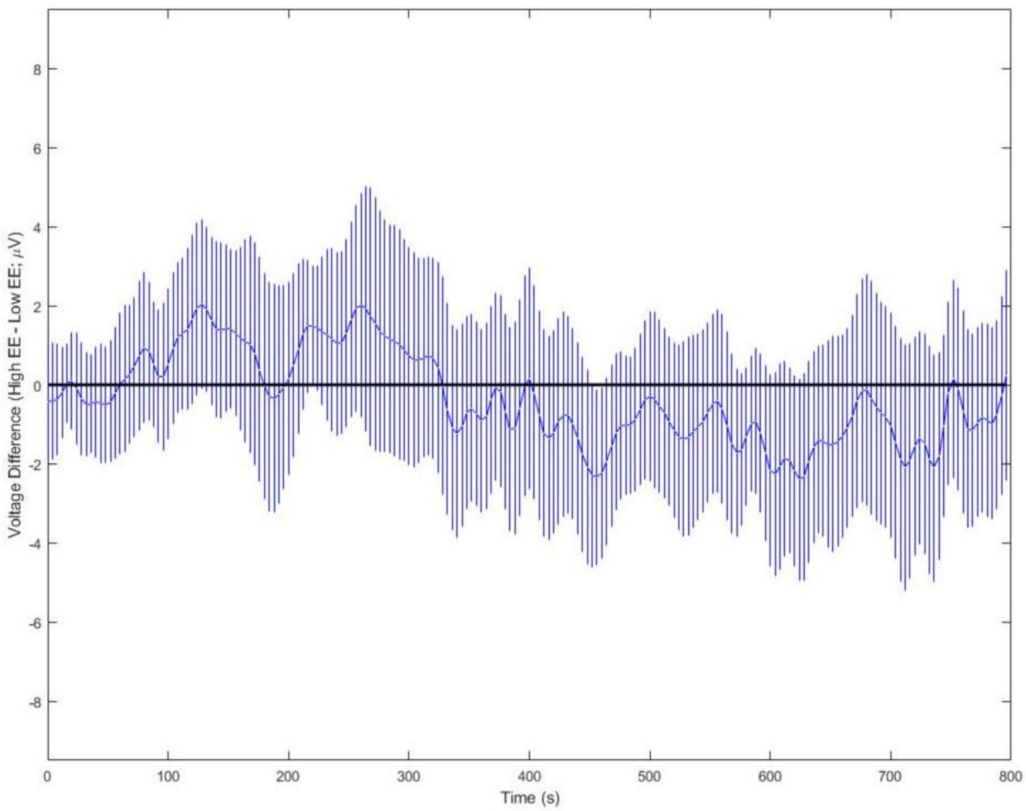

Figure 24. Difference waveform (High EE – Low EE) for electrode 14 in Experiment 3. Error bars are 99% Bayesian credible intervals.

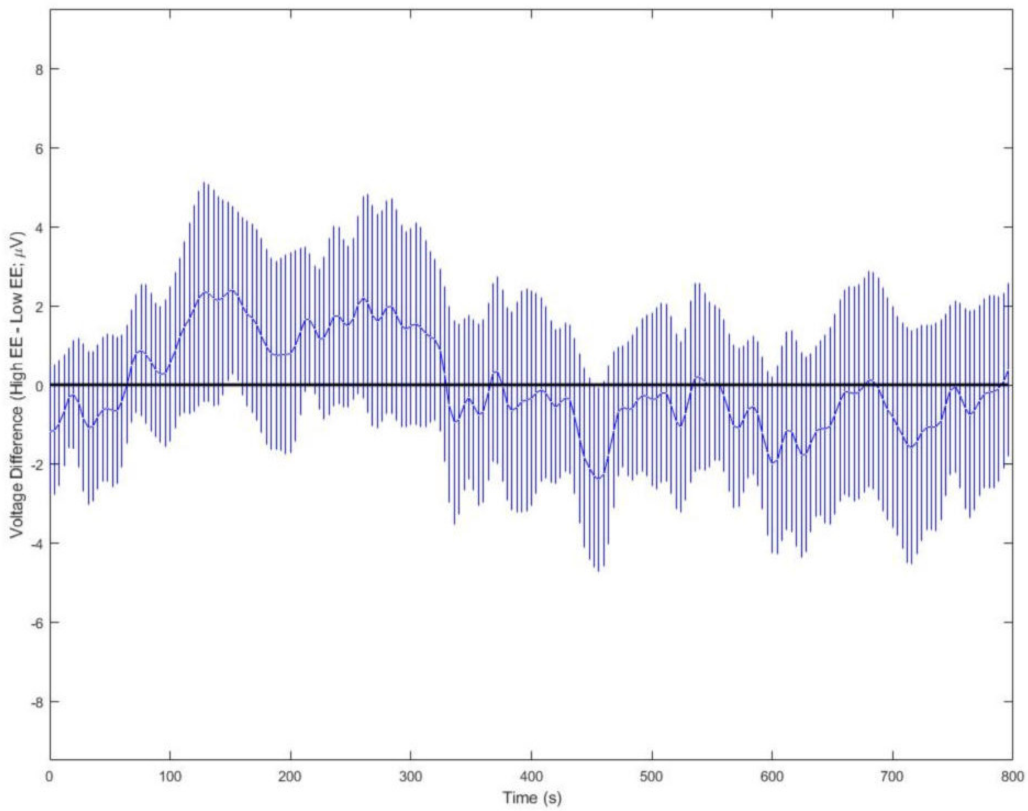

Figure 25. Difference waveform (High EE – Low EE) for electrode 16 in Experiment 3. Error bars are 99% Bayesian credible intervals.

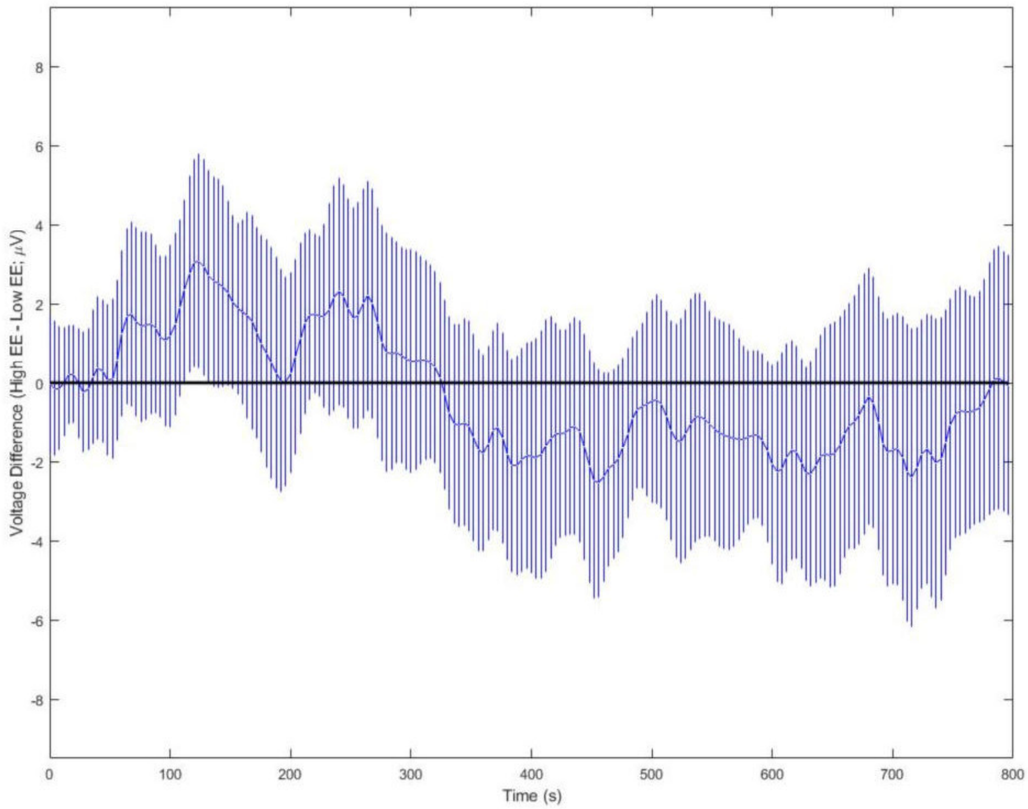

Figure 26. Difference waveform (High EE – Low EE) for electrode 24 in Experiment 3. Error bars are 99% Bayesian credible intervals.

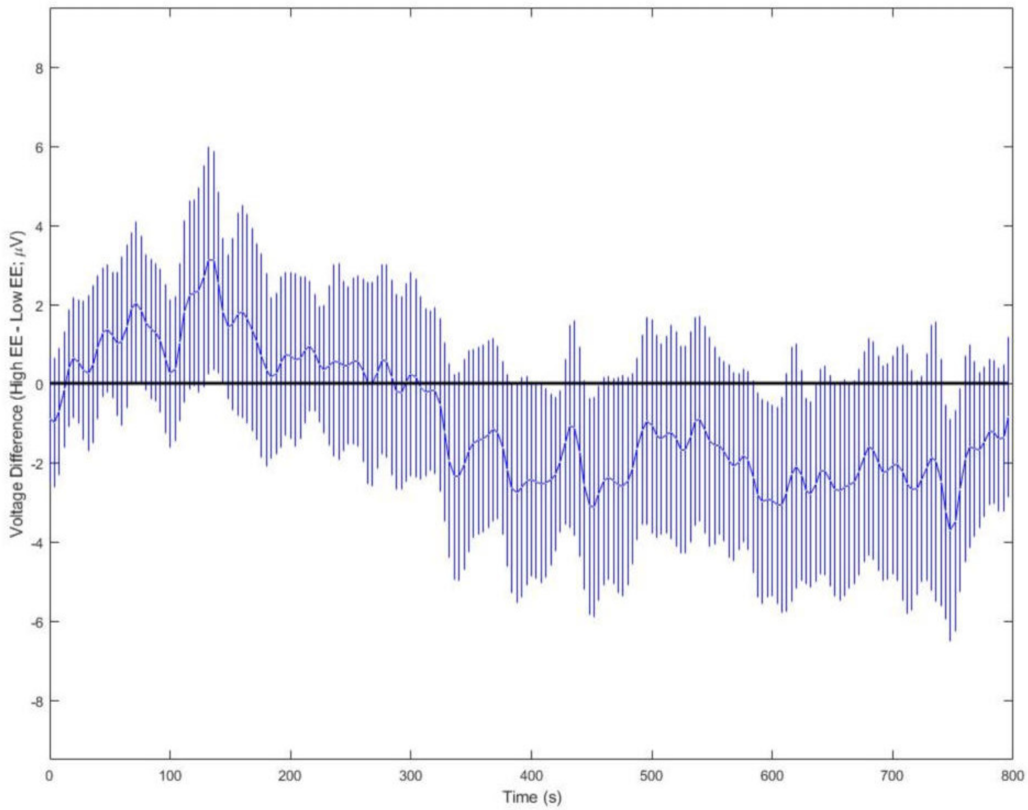

Figure 27. Difference waveform (High EE – Low EE) for electrode 25 in Experiment 3. Error bars are 99% Bayesian credible intervals.

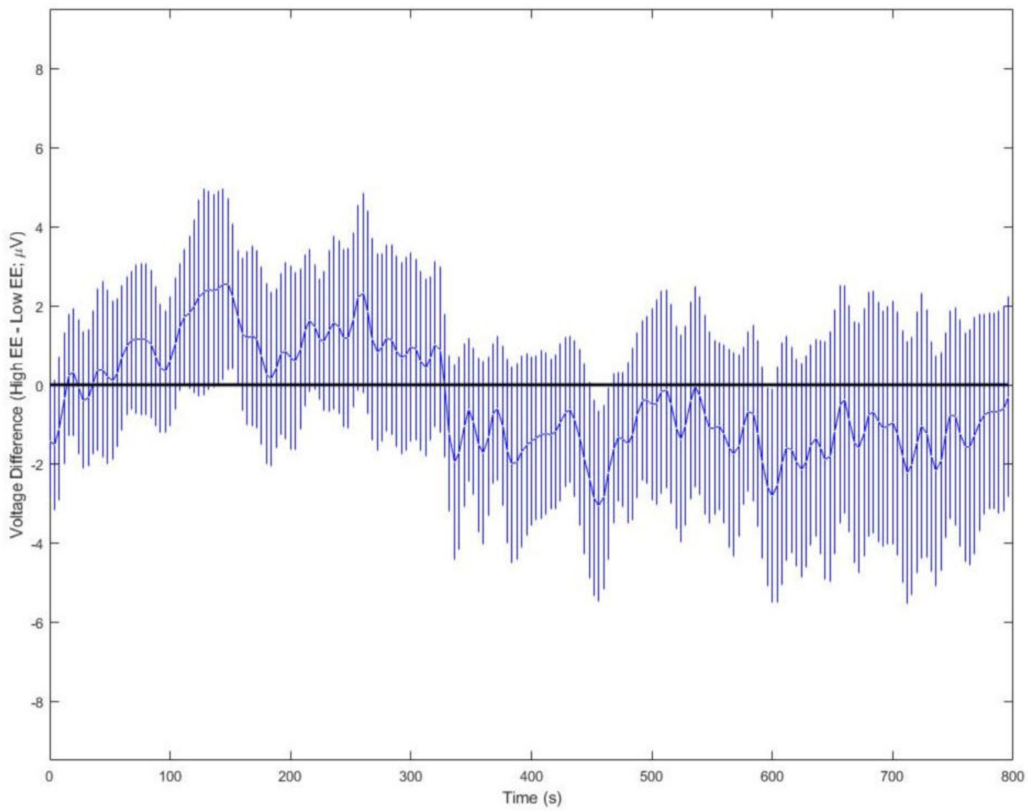

Figure 28. Difference waveform (High EE – Low EE) for electrode 26 in Experiment 3. Error bars are 99% Bayesian credible intervals.

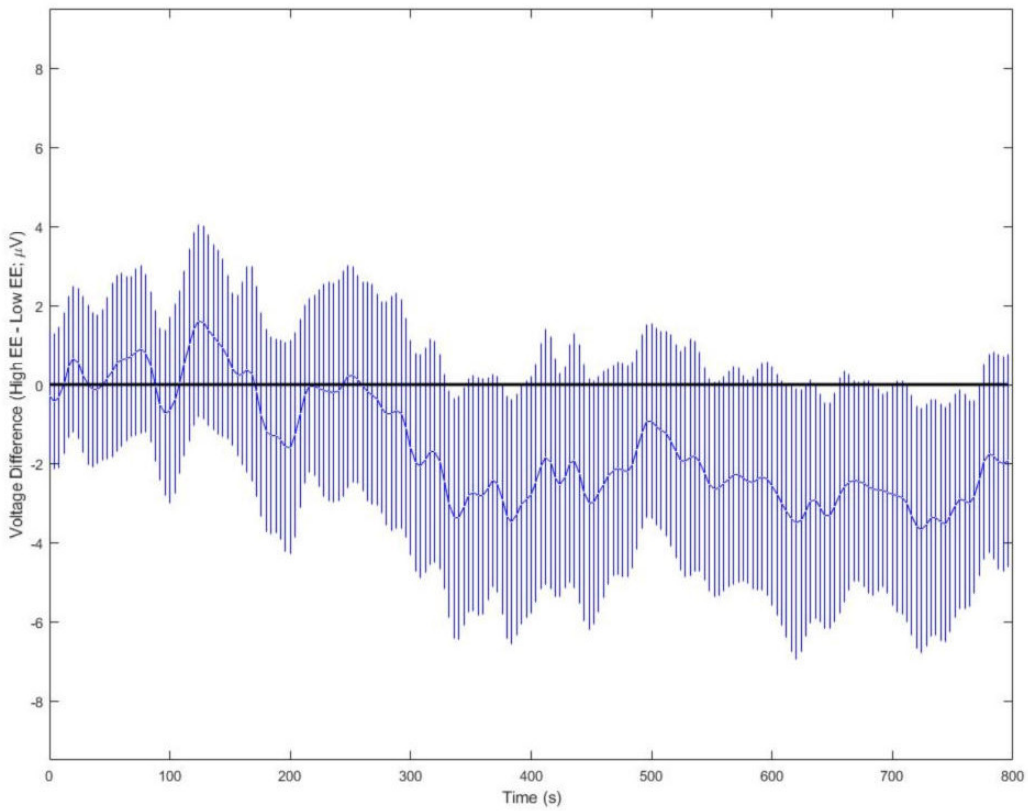

Figure 29. Difference waveform (High EE – Low EE) for electrode 29 in Experiment 3. Error bars are 99% Bayesian credible intervals.

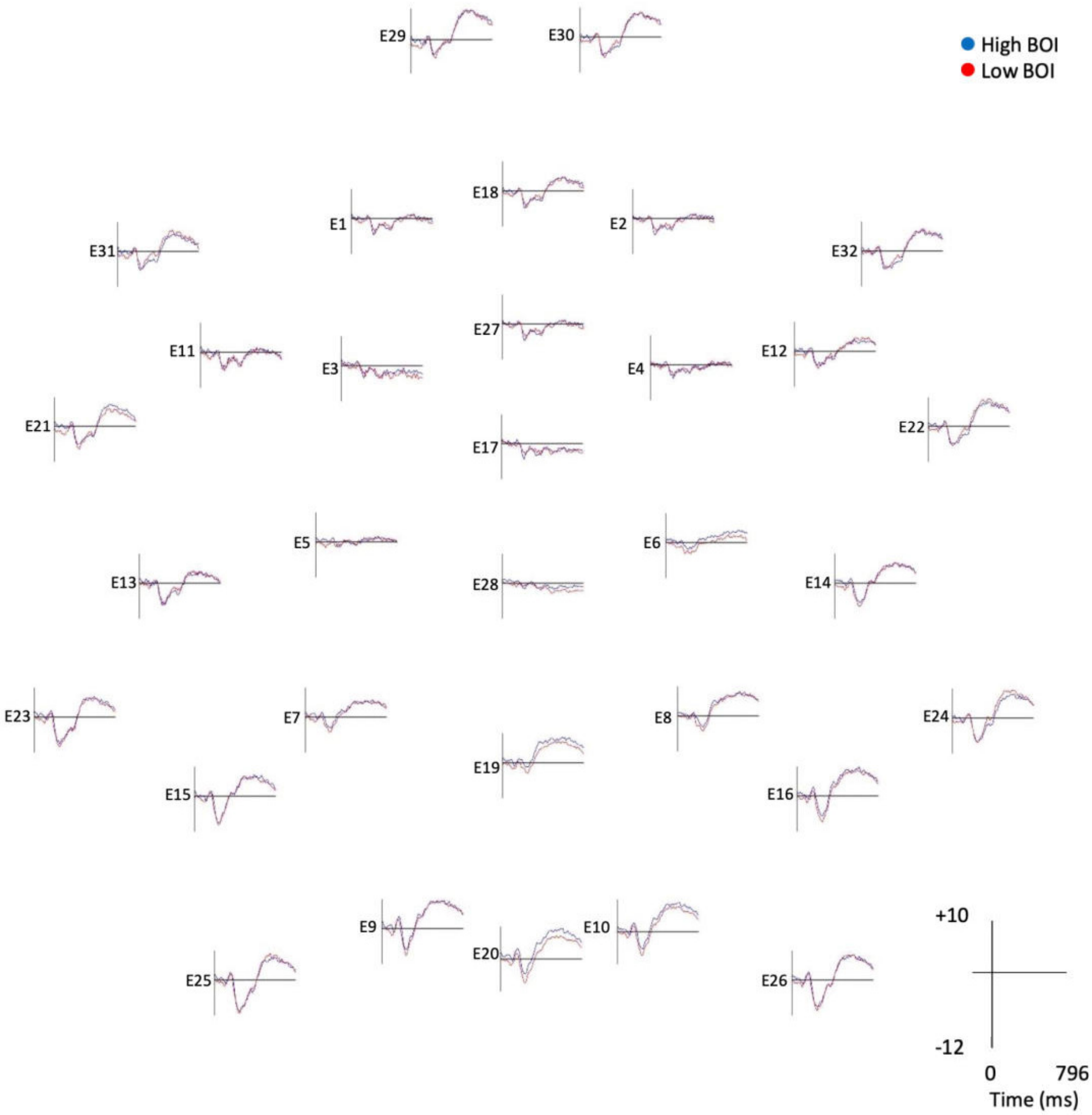

Figure 30. Topographic display of all ERP waveforms for Experiment 4 with all electrodes aligned as per Figure 13.

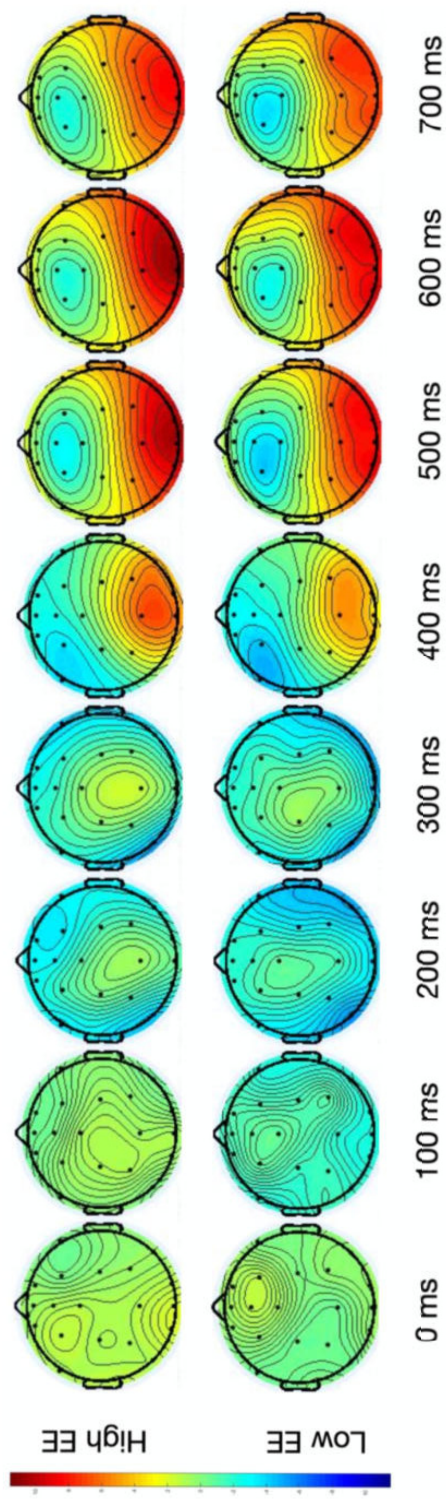

Figure 31. Topographic scalp plot for Experiment 4. Times (ms) are time since stimulus presentation. Red denotes positivity and blue denotes negativity. Scale is -10 to 10 μV.

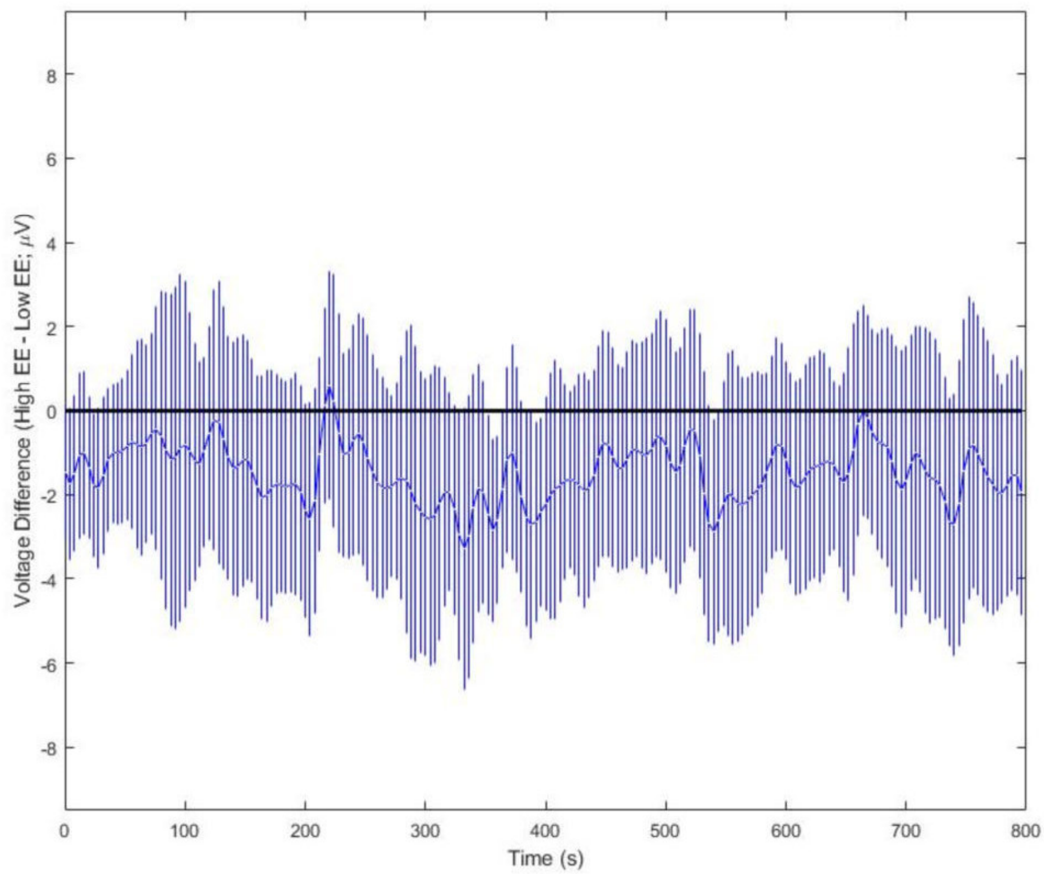

Figure 32. Difference waveform (High EE – Low EE) for electrode 3 in Experiment 4. Error bars are 99% Bayesian credible intervals.

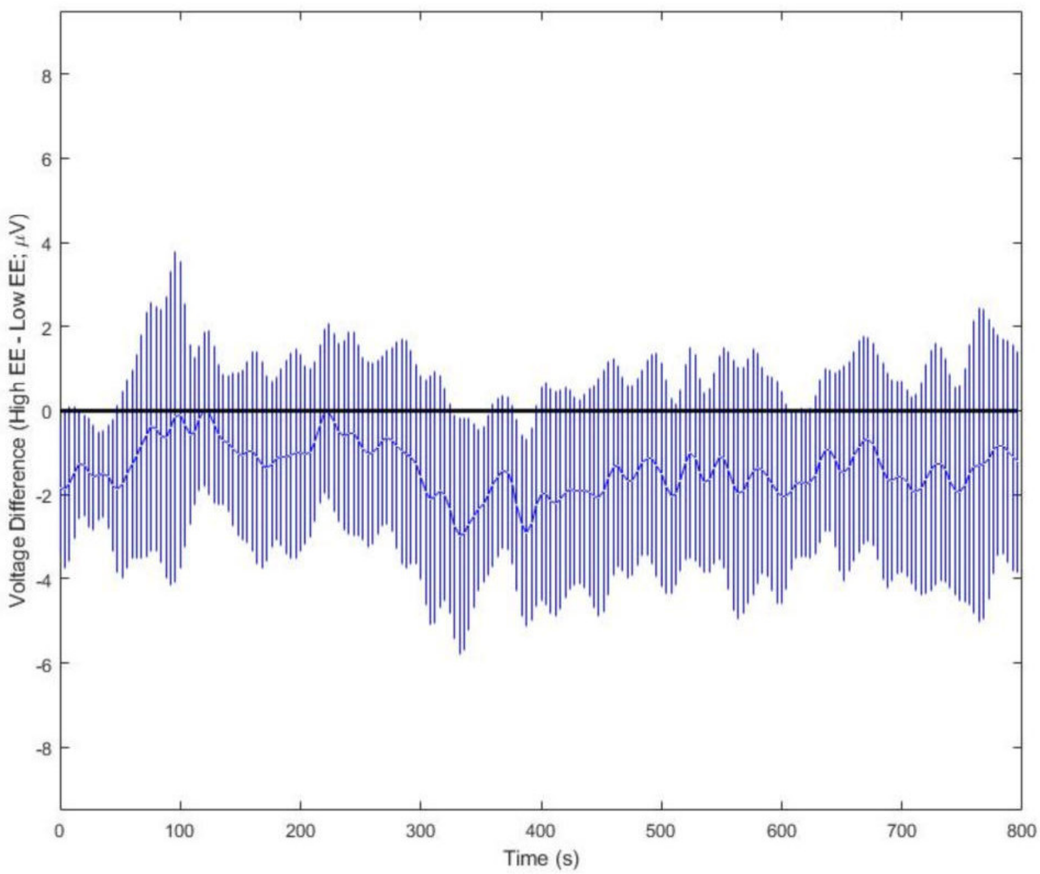

Figure 33. Difference waveform (High EE – Low EE) for electrode 5 in Experiment 4. Error bars are 99% Bayesian credible intervals.

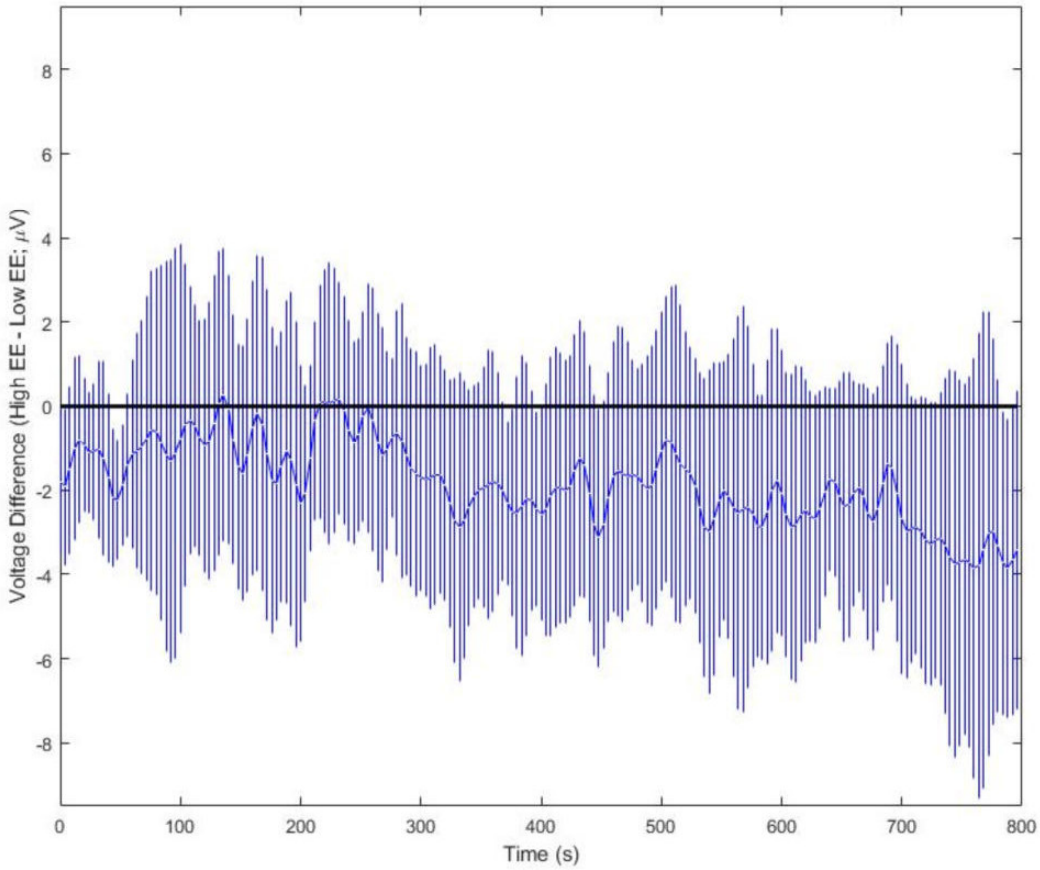

Figure 34. Difference waveform (High EE – Low EE) for electrode 11 in Experiment 4. Error bars are 99% Bayesian credible intervals.

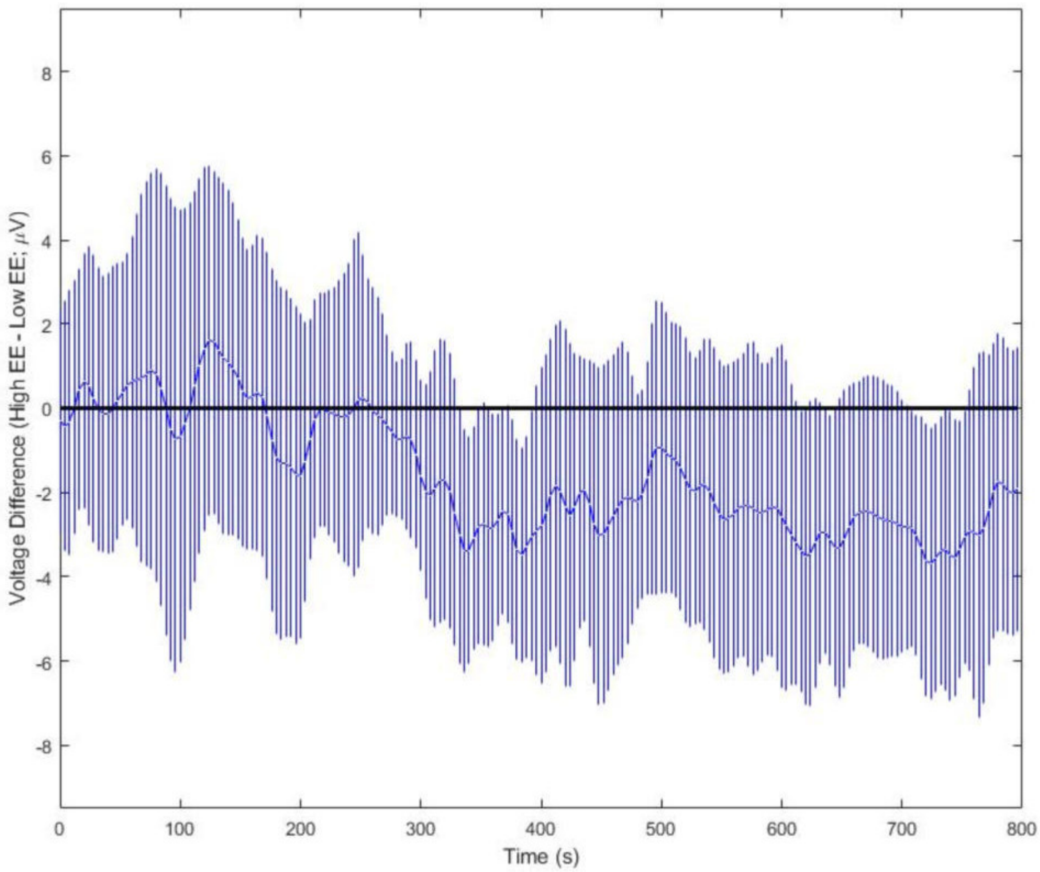

Figure 35. Difference waveform (High EE – Low EE) for electrode 29 in Experiment 4. Error bars are 99% Bayesian credible intervals.

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CHAPTER 5:

Conclusion

In the preceding chapters, grounded cognition hypotheses of conceptual processing were tested by analyzing behavioural, functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG) data. Participants completed a lexical decision task (LDT) and three semantic categorization tasks (SCTs). All experiments used a go/no-go procedure wherein participants, when presented with a letter string, pressed the spacebar if the letter string satisfied that experiment's decision criterion and did not respond if the letter string did not satisfy the decision criterion. This procedure was used to allow for the examination of the brain and behaviour patterns associated with the processing of grounded semantic dimensions of conceptual knowledge. An inter-trial interval of 15 seconds was used for all experiments. Doing so ensured that task-related hemodynamic changes could return to baseline between trials and to strengthen confidence that any behavioural data were not the product of experimentally induced priming effects. Collectively, these data replicate and extend previous observations in grounded semantic research, while also applying novel experimental, technological, and statistical methods to the field.

Behavioural Results

In the LDT it was hypothesized that high frequency words would be responded to more quickly and accurately than low frequency words. In the imageability and abstract noun SCTs it was predicted that participants would respond more quickly and accurately to words rated high in grounded semantic richness (body-object interaction (BOI) and emotion experiences (EE), respectively) than words rated low on the same dimensions. This is because, for imageable nouns, it was hypothesized that one's physical interactions with the words' referents would be automatically retrieved through grounded activation and simulation during task performance, because such bodily experiences play an important role in how concrete nouns are learned and retrieved from memory. For abstract nouns, it was hypothesized that one's emotion experiences with the words' referents would be similarly automatically activated during task performance, because such emotion experiences play an important role in how abstract nouns are learned and retrieved from memory. In summary, when reading a word rated high in grounded semantic richness, it was anticipated that the additional activation of bodily and emotion information should, in theory, facilitate participants' efforts to recognize the target word as an imageable or abstract noun, thereby resulting in shorter response latencies and higher accuracy.

In the concrete noun SCT, it was hypothesized that concrete nouns rated high in EE would be responded to less quickly and less accurately than those rated low in EE. Grounded emotion information was hypothesized to be inhibitory in the concrete noun SCT because, unlike in the abstract noun SCT described above, *concrete* nouns are thought to be learned and experienced during memory retrieval as a function of *bodily* experiences, not emotion experiences. Therefore, it was anticipated that during the concrete noun SCT, when the grounded emotion experiences associated with a concrete noun were automatically and implicitly activated, high levels of EE would be experienced as an abstract noun more than as a concrete noun. Despite having higher levels of grounded semantic richness, concrete nouns with high levels of EE would therefore require additional processing to resolve the discrepant emotion information (i.e., as compared to information indicating it is a concrete word). Consequently, the additional processing should, in theory, slow participant responses and increase the likelihood of incorrect responses.

The behavioural findings from the three SCT experiments described above support the hypothesis that grounded dimensions of semantic richness are automatically and implicitly activated during SCT performance regardless of their task relevance. They also supported the response latency and accuracy hypotheses and extended previous observations regarding the relationship between task-relevance and the influence of grounded semantic richness on SCT performance. The dimensions of grounded semantic richness that were manipulated in these experiments were not explicitly necessary to successfully complete the experimental tasks. As such, observing latency and accuracy differences that vary as a function of the manipulated variable suggests that grounded semantic information is implicitly and automatically analyzed when retrieving conceptual knowledge. For example, in the imageability SCT, where go-trials varied in BOI ratings, participants were only required to assess whether they could easily imagine a presented word's referent. There was no need to consider whether they had previous physical interactions with that referent. Participants responded more quickly and accurately to words rated high in BOI, which strongly suggests that participants were automatically accessing task-irrelevant bodily information. These data provide evidence that information obtained through one's sensory, motor, and emotional experiences with the environment is part of how people represent and access conceptual knowledge.

In addition to the response latency and accuracy data, these four experiments offer two further contributions to the field. First, a 15-second inter-trial interval (ITI) is atypically long compared to conventional SCT experiments. Such a long ITI was chosen to allow for hemodynamic changes to return to baseline between trials, and it also allows for a unique observation of SCT performance. In conventional SCTs with comparatively rapid stimulus presentation (e.g., every 1-3 seconds) it is possible that response time differences may be due, at least in part, to a priming effect. For example, in an abstract noun SCT, participants may be primed for *abstractness* by a single trial, and still benefit from such a priming effect when the next trial starts. As a result, response time differences may be amplified accordingly. However, by waiting 15 seconds between each trial, it is less likely that this sort of priming would influence participant responses. Furthermore, the response latency effect found in the concrete noun SCT is a novel finding. These new patterns of data observed with slow ITIs suggest that this experimental design is a valid method that provides insight into the nature of human conceptual processing.

Finally, the analytical methods adapted to these experiments are worthy of note. Oftentimes, neurophysiological data are segmented, averaged, and subsequently analyzed using frequentist statistics. In the experiments presented here, high-density Bayesian credible intervals were used to show *when* condition differences exist *across time*, with no data lost to averaging across pre-established temporal epochs. This technique provides a powerful tool for the analysis of time course data as it does not suffer the risk of committing a Type I error when calculating a great number of difference scores. Presenting the full time course of difference waves fit with high density Bayesian credible intervals allows people to identify the presence, timing, and strength of condition differences—typically with just a glance at each interval. Rather than making a binary decision regarding the rejection of a null hypothesis, the analytical methods adapted in the experiments presented here allow for meaningful discussion of the presence and nature of condition differences. Future research would increase the validity and accessibility of neuroimaging analyses by adopting such techniques, particularly in light of the growing evidence that ERP components do not each reflect distinct singular brain processes.

Near Infrared Spectroscopy

fNIRS was employed in this research to investigate activity in the prefrontal cortex (PFC) due to conceptual processing as operationalized by comparative changes in the concentrations of oxygenated hemoglobin ([O_2Hb]), deoxygenated hemoglobin ([HHb]), total hemoglobin ([THb]), and regional tissue oxygen saturation (Sat%). In the LDT, where the decision criterion was “Is this a real word?” and all go-trials varied in printed word frequency, visual inspection of the fNIRS data suggested that task-related activity primarily occurred in the left PFC. Specifically, approximately 4 seconds after stimulus presentation, decreases of [O_2Hb] and Sat% were evident along with an increase of [HHb] for no-go and low-frequency trials. This observation was interpreted as a general pattern of effort associated with lexical processing and served to guide the interpretation of the SCT data.

In the imageable noun SCT, visual inspection of fNIRS data revealed two different patterns. First, in the left hemisphere, increased Sat% was observed for low-BOI trials, and decreased Sat% was observed for high-BOI trials. This pattern was interpreted similarly as for the LDT, namely, that greater levels of semantic processing are evident in the left PFC. Second, increased [O_2Hb] was observed in the right hemisphere for low-BOI and no-go trials. This pattern was interpreted as increased processing to inhibit automatically generated responses. That is, after a long ITI, the presentation of a stimulus may automatically generate a behavioural response code in the brain, and no-go trials would require that response code to be fully inhibited. Concrete nouns rated low in BOI have less grounded semantic richness, or diagnostic information (i.e., less experience of physically interacting with the word’s referent), and likely were at least partially inhibited before participants fully recognized the word as an imageable concrete noun. This interpretation is supported by the response latency data discussed above.

In the abstract noun SCT, visual inspection of the fNIRS data suggested the same two patterns of data as were observed for the imageable noun SCT. First, bilateral [THb] and [O_2Hb] increases were observed for low-EE trials compared to high-EE trials. This pattern was interpreted as above: additional processing required for atypical task exemplars evident in the left PFC, and inhibitory effects no-go and low-EE trials in the right PFC.

However, in the concrete noun SCT, PFC hemodynamic activity was located primarily in the right hemisphere. Specifically, [O_2Hb] increases were observed for all three conditions, suggesting that processing of concrete nouns may occur in the right hemisphere more than the left. Additionally, [HHb] decreases were most evident for high EE trials, suggesting additional inhibitory processing for these atypical concrete nouns. The comparative lack of left PFC activity may have been due to the comparative ease of this experiment. That is, due to their grounded nature, concrete nouns may be easier to identify than are abstract nouns.

Across these four experiments, the general pattern of the fNIRS findings appeared to be the following. The processing of lexical stimuli produces [O_2Hb] increases in the left hemisphere of the PFC. The processing of abstract concepts appears to activate the left hemisphere more than the right hemisphere whereas, in contrast, the processing of concrete concepts appears to activate the right more than the left. Right hemisphere increases in [O_2Hb] may reflect the inhibition of automatically generated responses as seen in no-go trials and atypical category exemplar trials. These patterns are congruent with previous research, thus strengthening confidence in the interpretations of the patterns described above.

Unfortunately, when condition differences were analyzed via 12-second time course difference waves plotted with Bayesian high density credible intervals, no statistically significant differences were evident. That is, these data could not be conclusively interpreted as reflecting differential PFC hemodynamic activity elicited by the variables manipulated in these experiments. While this was disappointing and unexpected given pilot data collected prior to this research program, the general pattern of hemodynamic activity in each experiment described above suggests that fNIRS is sensitive to cognitive processing in the PFC. However, as discussed more fully in Chapter 3, several reasons exist as to why condition differences were not observed here. First, it is possible that the experimental manipulations were not challenging enough to elicit activity in the anterior PFC. Second, given the small size of the effects, it is possible that these experiments lacked statistical power to capture the effects. Third, it is possible that operationalizing emotion information as EE instead of valence resulted in an averaging-out of the effects, as other researchers have reported hemispheric PFC differences for positively and negatively valenced stimuli. Finally, it is possible that, in collecting fNIRS data concurrently with EEG data, employing an elastic electrode cap and cohesive tape for ~90-minute sessions led to optode shifting and subsequent data degradation that interfered with analyses. In light of the behavioural data discussed above, it can be concluded that the experimental manipulations (i.e., manipulations of grounded semantic richness dimensions) were successful. As such, it appears to be the case that fNIRS recordings from the anterior PFC in these experiments did not capture these processing differences.

Electroencephalography

EEG was employed in the SCT experiments to test the hypotheses that electrical brain activity will vary qualitatively and quantitatively as a function of the grounded nature of conceptual knowledge that an individual is processing. That is, rather than a single amodal knowledge centre activating to retrieve all general knowledge, different patterns of brain regions were hypothesized to contribute to conceptual processing as a function of the lived experiences associated with those concepts. Scalp topography was inspected along with the P200, N400, and P600/N600 deflections.

The amplitude of the P200 component is generally associated with task difficulty (greater amplitudes for harder trials) and the automatic evaluation of stimuli. Greater amplitudes were observed in the imageability SCT for low BOI trials, in the abstract noun SCT for low EE trials, and in the concrete noun SCT for high EE trials. This pattern suggests that these trial types automatically and immediately required more effort to process. When examining the topographical pattern of activity across these experiments, however, the P200 was observed primarily in posterior regions in the imageability SCT, while occurring in left frontal regions in the abstract and concrete noun SCTs. That this component occurs in different locations in different experiments but occurs at the same time—and is of greater magnitude compared to 'hard' trials in all experiments—suggests that the P200 component is not a singular entity. Rather, electrical brain activity during this time reflects an automatic level of effort being exerted to process a presented stimulus in the context of current task demands and that grounded dimensions of grounded semantic richness are automatically activated and influence task difficulty.

The N400's amplitude is often interpreted as reflecting the amount of effort necessary to integrate stimulus information into current task demands. In the abstract and concrete noun SCTs, the N400 occurred primarily in left frontal medial regions, with more extreme negativity for low EE trials. This suggests that the N400 in these experiments reflects the processing of EE itself, regardless of task relevance, with higher levels of EE producing greater levels of processing. In the imageability SCT, the N400 was most evident in the frontal right hemisphere and appeared to occur later than it did in the concrete and abstract noun SCTs. This suggests that the nature of information being contextually analyzed during the N400 varies as a function of semantic variables being analyzed and that, similar to the P200, the N400 is not a discrete singular component. Rather, negative deflections occurring around this time appear to reflect the actual processing of semantic variables themselves.

The later deflections showed condition differences as well. In the imageability SCT, condition differences were observed in the right parietal region, while occurring in the left temporal region in the abstract and concrete noun SCTs. Additionally, more pronounced deflections were observed for irregular stimuli (low BOI nouns, low EE abstract nouns, and high EE concrete nouns). As the P600 is generally interpreted as reflecting additional processing of incongruities between a stimulus and current task demands, these data support previous observations of these deflections in semantics research.

The EEG data recorded in these experiments supports the hypotheses that information obtained from bodily experiences is part of one's representation of conceptual knowledge and that this information is activated automatically during conceptual processing as evidenced in qualitative and quantitative ERP differences. Although the semantic dimensions of BOI and EE did not necessarily need to be activated in the SCTs for successful task completion, differences between high- and low-richness trials were evident in ERP deflections regardless of task relevance. Amplitude and scalp topography differences in event-related electrical brain activity support the hypotheses that grounded information is integral to one's representation and processing of conceptual knowledge.

Conclusions

The EEG data presented in Chapter 4 demonstrate differing patterns of brain activity as a function of the automatic activation of task-irrelevant dimensions of grounded semantic richness associated with grounded experience, even when those dimensions are incongruent with current task demands. Although no statistically significant condition differences were obtained via the fNIRS measurements reported in Chapter 3, the patterns of activity observed were congruent with grounded hypotheses. Further research will be needed to validate an event-related fNIRS methodology when studying semantic processing in the PFC.

Collectively, the four experiments presented in this dissertation support the claim that conceptual knowledge is at least partly grounded in sensorimotor and emotion experience. Conceptual knowledge is processed more quickly and accurately when current task demands are congruent with the automatic reactivation of brain regions generally associated with the experiences of typical categorical exemplars. Extending beyond this, however, the data presented here convincingly demonstrate that grounded information obtained through physical, sensory, and emotional experiences with categorical members is automatically reactivated during conceptual processing even when doing so interferes with successful and timely task completion.