Grasping the Idea – With Your Hands?

A tDCS Investigation of Embodied Simulation in Motor Metaphors

BY

FELIX S. PAMBUCCIAN
B.S., University of Minnesota – Twin Cities, 2013
M.A., University of Illinois at Chicago, 2017

DISSERTATION

Submitted as partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Psychology
in the Graduate College of the
University of Illinois at Chicago, 2021

Chicago, Illinois

Defense Committee:

Gary Raney, Chair and Advisor
Eric Leshikar
Kara Morgan-Short
Natalie Parde, Computer Science
Bodo Winter, University of Birmingham

This dissertation is dedicated to my father, Stefan E. Pambuccian (1957-2020). Thank you for everything you have done for me. I will do my best to live up to your example of intellectual honesty, rigor, and kindness as I move into the next stage of my life.

ACKNOWLEDGMENTS

I would like to thank my dissertation committee – Gary Raney, Kara Morgan-Short, Eric Leshikar, and Natalie Parde – for their support, feedback, and help throughout the process of planning and executing this study. I would like to especially thank my advisor, Gary Raney, for his support and patience not only throughout the process of completing my dissertation, but throughout my entire time in graduate school.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

A study of whether motor simulations are activated when action words are used literally and nonliterally was carried out using a neurostimulation methodology. Transcranial direct current stimulation (tDCS) was used to increase neuronal excitability in the left primary motor cortex while participants (N = 55) read short sentences and judged whether each sentence made sense. Participants read four categories of sentences: literal motor sentences (e.g., *the architect grasped the pen*), literal non-motor sentences (e.g. *the student understood the idea*), nonsense sentences (e.g. *the man browsed the* ball), and motor metaphors (e.g., *the student grasped the idea*), which varied in familiarity.

Neurostimulation (anodal TDCS) significantly facilitated processing of literal motor sentences and motor metaphors, but not literal non-motor or nonsense sentences. Within motor metaphors, neurostimulation significantly facilitated processing of unfamiliar but not familiar expressions.

These results indicate that embodied motor simulation facilitates processing of both literal and figurative uses of motor action words, suggesting that the figurative meaning is grounded in the literal meaning. In motor metaphors, the importance of embodied simulation decreases as familiarity increases, suggesting that the embodied pathway is eventually replaced with faster, non-embodied processing pathways as familiarity increases

I. INTRODUCTION

A. **Background**

Reading descriptions of literal motor actions, as in the phrase *she grasped the pen*, causes activation in areas of our motor and premotor cortices that correspond to hand and finger motion (Hauk et al., 2004; Tettamanti et al., 2005). According to theories of embodied cognition (Barsalou, 1999), this activation occurs because reading about motor actions triggers sensory simulation of the motor action referenced in the text – a kind of "partial re-experiencing." Recent research has posed the question: given that embodied motor simulations are activated when reading descriptions of literal actions (e.g., *grasped the pen*), are motor simulations similarly activated when action words are used nonliterally, as in the motor metaphor *she grasped the idea*?

This question has important implications for language processing. For instance, if metaphoric uses of action words activate embodied motor simulations, this may suggest that the metaphoric meaning of action words like *grasp* is grounded in the literal meaning. By contrast, if metaphoric uses of action words do not activate embodied motor simulations, this could indicate that figurative meanings are separate and unrelated to the literal meanings. The question of whether embodied simulations are involved in metaphor processing also has important implications for theories of cognition. To provide the background needed to understand the implications of this question, and the research that has addressed it, I will begin by reviewing literature on embodied cognition and metaphor processing.

B. **Embodied Cognition**

Embodied cognition is a relatively new set of ideas about the relationship between body and mind, informed by research in psychology (e.g. Barsalou, 1999), philosophy (e.g.

Churchland et al., 1994), and robotics (e.g. Brooks, 1991). Among the most influential theories of embodied cognition is Barsalou's (1999) model, which systematically explains how the body's perceptual inputs serve as building blocks for higher cognition. To understand this model of embodied cognition it is helpful to provide a contrast with a traditional view of cognition.

The traditional view of cognition makes extensive use of a "computer metaphor," which imposes strict separation between the "software" of the mind and the "hardware" of the body and brain (Block, 1995). On this view, cognitive processes operate on abstract, symbolic mental representations that serve as the basic components of cognition. These symbols bear arbitrary relation to any perceptual (bodily) inputs they might use, meaning that modality-specific information (e.g., sight, sound, touch) must be converted into this abstract, amodal symbolic language (Niedenthal et al., 2005). Because the physical body has no influence on the symbolic language of cognition, it follows that human cognition could theoretically be replicated outside the human body and brain, for instance on nonbiological hardware like computer chips (given the technological ability).

By contrast, Barsalou's (1999) model of embodied cognition eliminates the need for information from the body's senses to be converted into abstract, amodal symbols. Instead, Barsalou proposed that holistic perceptual experience is broken down into perceptual components and then stored in perceptual symbols – a language of cognition that retains components of perceptual experience. Barsalou's model proposes that during higher cognition, association areas of the brain partially reactivate sensorimotor areas to implement these perceptual symbols. This partial reactivation of sensorimotor areas is referred to as "sensorimotor simulation" of the action or experience a person is thinking about. As an example, consider the action of throwing a ball. The experience of throwing a ball is broken down into individual sensorimotor components (e.g., visual components and motor components) and stored in perceptual symbols. Later, thinking about throwing a ball partial reactivates visual and motor brain areas associated with these perceptual components (sensory simulation of throwing). Thus, in the embodied cognition view, the body and its sensorimotor inputs are central aspects of cognition.

Barsalou and others have suggested that even complex mental phenomena and abstract concepts rely on perceptual symbols and sensory simulation. For instance, Wilson (2002) proposed that the experience of empathy may be grounded in mental recreation of another person's feelings in ourselves, beginning with embodied simulation of basic sensations they may be experiencing. However, skepticism regarding the idea that embodied cognitive processes can account for the full range of human cognition has led to the proposal of alternative "hybrid" models (Mahon & Caramazza, 2008; Pulvermüller et al., 2009). In these models, complex cognitive processes such as language processing and problem solving involve the integration of both embodied and nonembodied cognitive processes.

It is important to note here that Barsalou's (1999) model is far from the only theory addressing embodied cognition or sensorimotor simulation. Embodied cognition can refer to a variety of phenomena, and even narrowing the scope to sensorimotor simulation, different models disagree on how sensorimotor simulation relates to other cognitive processes. However, the existence of the phenomenon that Barsalou calls sensorimotor simulation is not debated, and the present study does not touch on debates about the role of sensorimotor simulation in general cognition or attempt to compare different models. As such, beyond noting their existence, I will not discuss other models of perceptual simulation and embodied cognitive processing.

Embodied cognition has been observed in text and language comprehension (Fischer & Zwaan, 2008). For example, researchers have observed activation in sensorimotor areas of the brain when participants read sentences describing body movements and actions (e.g., Hauk et al., 2004; Tettamanti et al., 2005). Importantly, the sensorimotor neural activity was congruent with the action type read in the text – for instance, areas of the motor cortex that control hand motion were activated when participants read verbs related to hand actions such as *grasp*. These findings suggest that activation of motor areas facilitated semantic processing of written descriptions of actions, consistent with the sensory simulation specified by models of embodied cognition (e.g., Barsalou, 1999). Such embodied simulation has also been observed when reading words related to sensations rather than motor actions. For instance, activation has been observed in taste-perception areas of the brain when presenting participants with individual taste-related words such as *sweet* and *bitter* (Citron & Goldberg, 2014; Speed & Majid, 2019)

The context in which a sensory or motor action word appears may also influence the embodied simulations that are activated in response. Kable et al. (2002; 2005) suggested that the task or sentence context may influence whether embodied simulations are engaged in response to action or sensory words. This is consistent with behavioral priming studies showing that activation of the specific meaning attributes of a word depends on sentence context. For example, in the sentence "The little boy shuddered eating a slice of lemon," only contextually relevant attributes of "lemon" (e.g., sour) were primed whereas contextually irrelevant attributes (e.g. yellow) were not (Tabossi, 1988; Tabossi et al., 1987). Such context effects appear to provide evidence against the idea proposed by some researchers (e.g. Pulvermüller, 2009) that embodied simulations are engaged automatically and reflexively in response to sensory or action words regardless of context. Overall, it appears that embodied motor and sensory simulations are influenced both by the presence of motor or sensory words and by the surrounding context. Logically, aside from potentially changing the reader's interpretation of the action or motor word, the surrounding context supplies important additional information. Because the same motor word can be used to describe a diverse set of actual motor actions, cues from the surrounding text may be needed to simulate a motor action in detail. For instance, detailed embodied motor simulation of "she threw the ball toward the outfield" may differ from "she threw the keys onto the counter," because, despite both phrases using the same action word, the type of motion described is different.

C. **Metaphors and Embodiment**

Embodiment refers to the idea that, in general terms, physical characteristics of an agent's body (and its interactions with the environment) influence cognition (Wilson & Foglia, 2011). The word *embodiment* is often used as a general umbrella term that includes many different ideas, including theories of embodied cognition. In this proposal, I use the term *embodiment* to refer to the nonspecific idea that aspects of the body and its sensory experiences influence human language and cognition (Gallese & Lakoff, 2005). By contrast, I use the term *embodied cognition* to refer to the more specific idea that embodied simulation of sensory and motor experience are key components of cognitive processes, as described by Barsalou (1999).

Metaphors have been studied as elements of language that reflect embodiment. In a seminal book, Lakoff and Johnson (1980) proposed that metaphors are not merely tools of expression, but that they are based on experience and reflect our conceptual systems. To support this idea, they considered the metaphoric mappings that underlie many figurative expressions used in everyday speech. For instance, the expression *you're wasting my time* might reflect the underlying metaphoric mapping TIME IS MONEY, whereas *the holiday season is behind us* and *the weeks ahead of us* rely on the metaphoric mapping TIME IS SPACE. Lakoff and Johnson called these underlying metaphoric mappings *conceptual metaphors*. A conceptual metaphor like TIME IS SPACE is composed of the target domain TIME and the source domain SPACE. The source domains of conceptual metaphors often reflect contexts that can be directly experienced through the body's senses, which are used to understand target domains that reflect abstract concepts (Lakoff & Johnson, 1980; Lakoff, 1999). In the earlier example, the more abstract target domain TIME is understood through spatial orientations behind/in front of the body (Boroditsky, 2000; Gentner, 2001). Based on the observation that many figurative expressions rely on mappings between concrete, experiential source domains and abstract target domains, Lakoff and Johnson (1980; 1999) proposed that metaphoric expressions are grounded in human interactions with their physical reality. According to Lakoff and Johnson (1980; 1999), metaphoric expressions reflect the fact that we conceptualize abstract concepts by relating them to concrete, experiential phenomena.

Some groups of metaphors have particularly clear embodied origins. For instance, expressions like *grasping the idea* rely on mappings between bodily sensations or motor actions (e.g., physical grasping, the source domain) and abstract concepts (e.g., understanding, the target domain). I discuss such expressions at length in the following sections of this paper. Certain metaphors that express emotion may also reflect embodiment. Some metaphoric expressions appear to communicate emotions by referencing bodily sensations that characterize the emotion, such as *he was paralyzed by fear* and *she was quivering with excitement* (Kövecses, 1986; 2000; Ding, 2012). These expressions seem to localize physiological sensations and reactions to specific sites on the body. For instance, the expression *she was flushed with anger* corresponds to the physiological effect of redness in the face and neck area, while the expression *he was* *getting hot under the collar* corresponds to the feeling of heat or increased body/skin temperature that accompanies anger (Ding, 2012). Cross-cultural investigations have shown remarkable similarities in such metaphoric expressions of emotion across different cultures and languages, which may support the idea that these expressions are grounded in basic physiological sensations. Cultures and languages across which such similarities have been found include Chinese (Yu, 1995, 1998), Tunisian Arabic (Maalej, 2004), Tahitian (Solomon, 1984), and Chagga, a Tanzanian language (Emanatian, 1995).

D. **Metaphors and Embodied Cognition**

As embodied cognition became an established area of research, the proposed embodied origins of metaphors saw renewed interest. Because these embodied origins are often seen in metaphoric source domains that reflect contexts that are directly experienced through the body's senses (Lakoff & Johnson, 1980), a logical connection to embodied cognition was to consider whether metaphor processing involves simulating the bodily experience referenced in the source domain.

How could embodied cognition be involved in metaphor processing? Some metaphoric expressions are based on underlying associative mappings that reflect bodily sensations or motor actions. For example, a metaphor like *he grasped the idea* is based on the underlying conceptual metaphor UNDERSTANDING IS HOLDING – a conceptual mapping between an experiential source domain (the motor action of physical grasping) and an abstract target domain (understanding). I refer to these figurative expressions with mappings between bodily sensation or motor action source domains and abstract target domains as *sensorimotor metaphors*. Researchers (e.g., Gibbs, 2006; Ritchie, 2008) have suggested that sensorimotor metaphors may be understood in part through embodied sensory or motor simulation of the metaphor's source domain. For instance, embodied simulation of the motor action of physically grasping an object with one's hand may occur when processing the expression *he grasped the idea*. Using neuroimaging techniques, this embodied simulation would be observable as activity in areas of the primary motor and premotor cortices associated with hand and finger movement. I refer to this idea that sensorimotor metaphor processing engages embodied cognition as the *ECSM hypothesis* (Embodied Cognition – Sensorimotor Metaphor hypothesis).

The question of whether metaphors are processed via embodied cognitive processes as suggested by the ECSM hypothesis might have important implications for the role of embodied cognitive processes in human cognition (Casasanto 2008; 2009). Although the idea that certain types of cognition (like imagining oneself performing physical actions) rely on embodied processes is widely accepted (Pulvermüller, 2005; Willems & Casasanto, 2011), it has been proposed that embodied cognition could account for a much broader range of cognition. Indeed, Barsalou (1999) proposes that all human cognition can be based on embodied cognitive processes. This includes abstract cognition, such as thinking about intangible ideas and principles. A difficult question thus emerges: how can embodied cognition - which draws on the body's sensory system - account for thinking about abstract concepts that cannot be seen, touched, or felt? Because embodied cognition involves simulation of experiential phenomena, arriving at abstract cognition from embodied simulation of sensory experience is a major challenge for pure embodied cognition models (Mahon & Caramazza, 2008).

Some theorists (e.g., Casasanto, 2008; 2009) have proposed that metaphoric expressions and their underlying metaphoric mappings may provide one possible answer. The metaphoric mappings that underlie expressions like *he grasped the idea* link sensory or motor source domains to abstract target domains, providing a mental bridge between bodily experiences and intangible concepts. These metaphoric mappings could serve as pathways in an embodied account of higher-order cognition: abstract cognition could begin with embodied simulation of sensory experience (e.g., simulation of physically grasping an object) and use these metaphoric mental pathways as bridges to abstract concepts like understanding, justice or freedom. Such metaphoric bridging has been suggested as a possible mechanism to enable embodied cognitive processes to produce abstract cognition (Casasanto, 2008; 2009).

The idea that embodied cognition could facilitate processing of sensorimotor metaphors may hold important implications for theories of cognition and language processing. This theoretical background has motivated several studies investigating the role of embodied cognition in sensorimotor metaphor processing. Although a small body of work has addressed metaphors with sensory source domains (e.g., taste; Citron & Goldberg, 2014), a larger body of work has addressed metaphors with motor source domains. I will focus specifically on metaphors that involve motor-related action words, such as *grasp* and *kick*.

Most studies investigating embodied cognition in response to motor metaphors (e.g., Boulenger et al., 2009; Desai et al., 2011) have used neuroimaging to monitor neural activity in response to metaphors. One recent study (Reilly et al., 2019) has used neurostimulation to inhibit motor cortex activity during metaphor processing, with the goal of establishing a causal link between neural motor activity and fluency in processing motor metaphors. In the following section, I summarize and evaluate the findings of several studies examining the role of embodied simulation in motor metaphor processing.

E. **Review of Studies Investigating Embodied Cognition in Motor Metaphors**

Several studies have used neuroimaging or neurostimulation techniques to investigate research questions related to embodied cognition in metaphor processing. In this section, I review ten studies relevant to this question. Of these studies, seven have reported results that support the idea that embodied simulations are involved in processing sensorimotor metaphors, as described in the ECSM hypothesis (Gibbs; 2006; Ritchie, 2008). The remaining three studies found no evidence of neural activity indicative of embodied cognition in response to sensorimotor metaphors.

Boulenger et al. (2009) used functional magnetic resonance imaging (fMRI) to record neural activity while participants read short sentences in which hand- and foot-related action words were used metaphorically or literally. Pairs of metaphoric and literal sentences were created for the experiment, with half of the pairs using foot-related action words (e.g., *literal: Pablo kicked the ball*; metaphoric: *Pablo kicked the habit*) and half using hand-related action words (e.g., literal: *John grasped the object*; metaphoric: *John grasped the idea*). Seventy-six pairs of experimental sentences were presented to participants (N =18) on a monitor, one word at a time, with each word being presented for 500 ms.

To investigate whether the sensorimotor system plays a role in semantic processing of metaphoric and literal sentences, Boulenger et al. (2009) analyzed neural activity in several regions of interest along the motor strip in the central and precentral motor cortex. The regions of interest were selected based on previous research measuring neural activation in response to reading descriptions of hand and foot motor actions (e.g. Hauk et al., 2004; Tettamanti et al., 2005). Boulenger et al (2009) found that relative to sentences with no motor action words, both literal and metaphoric sentences elicited increased neural activity in motor strip areas, with either hand or foot areas of the motor strip showing increased activation corresponding to the action word in the sentence. Boulenger et al. interpreted this result as supporting the idea that the sensorimotor system plays a role in semantic processing of metaphoric phrases motor source domains, consistent with the ECSM hypothesis (Gibbs, 2006; Ritchie, 2008). Moreover, for both metaphoric and literal sentences, the observed motor strip activity did not appear to be a reflexive response to a single critical action word (e.g. the word *kick* in *Pablo kicked the habit*), but rather peaked at a later time, after the entire sentence had been read. This suggests that embodied motor simulation was not simply a reflexive response to action-related words but rather a key process that facilitated semantic processing of the sentence, whether metaphoric or literal.

Boulenger et al. (2012) performed a follow-up study using magnetoencephalography (MEG) imaging that allowed for more precise measurement of the timescale of neural activation. Aside from using a different neuroimaging technique, this study's methodology was largely identical to Boulenger et al. (2009), using the same set of literal and metaphoric sentence stimuli, the same instructions, and the same presentation format and time interval. Results (N = 18) indicated that the motor cortex showed activation early in sentence processing, within 250 ms following the critical action word, reaching peak activation at 650-700 ms after the action word (the latest time window analyzed). These results further support the idea that embodied motor simulation plays a role in processing of both literal sentences and motor metaphors.

Lauro et al. (2013) conducted an fMRI study and measured neural activity in response to literal and metaphoric sentences. Lauro et al. used 21 hand/arm related action verbs (e.g., throw) and 21 foot/leg related verbs (e.g., stumble) to generate literal (e.g., *Marco throws the wood in the fireplace*), metaphoric, (e.g. *Matilde kicked the habit of smoking*) and idiomatic sentences (e.g. *The old man finally kicked the bucket)*. The distinction made in this study between metaphoric and idiomatic uses of action words is important. In action metaphors (e.g. *kick the habit*), the action word is relevant to the underlying metaphoric mapping (e.g. a mapping between the action of *kicking* and the concept of stopping or getting rid of something) and is thus conceptually related to the meaning. By contrast, most idioms (e.g. *kick the bucket*) do not have such an underlying metaphoric mapping (Davies, 1982; Hanks, 2004), and thus the action word is not part of a metaphoric mapping that reflects the expression's meaning. Lauro et al. presented each sentence for 2500ms and participants (N = 24) were instructed to read the sentences normally. Results showed that both literal and metaphoric sentences activated hand and foot areas of the motor cortex. However, much stronger activation was observed in these areas for literal sentences compared to metaphorical sentences. No significant motor cortex activation was observed for idiomatic sentences. Because activity indicative of embodied simulation was found for metaphors, but not for idioms (which lack an underlying metaphoric mapping), this result supports the ECSM hypothesis.

Desai et al. (2011) used fMRI to measure neural activity in primary motor areas (motor cortex) and in the anterior inferior parietal lobule (aIPL), a neural area involved in motor action planning. Three types of matched sentence stimuli were presented: literal, metaphoric, and abstract. Literal sentences described a human agent performing a hand/arm motor action (e.g., *The daughter grasped the flowers)*. The corresponding metaphoric sentence used the same hand/arm action verb in a figurative manner (e.g., *The public grasped the idea*). The corresponding abstract sentence had a similar meaning to the metaphoric sentence but used a non-action verb (e.g., *The public understood the idea)*. For each sentence, the noun phrase (e.g., *The public*) was presented for 500 ms and the remainder of the sentence (e.g., *grasped the idea)* was presented for 1300 ms. Participants (N = 22) were presented with 81 sentences of each type and instructed to read the sentences normally. A separate group of participants (N = 28) rated each sentence on familiarity using a 1-7 scale.

Desai et al. (2011) hypothesized that relatively unfamiliar motor metaphors would most strongly engage the neural sensorimotor system because comprehension of unfamiliar expressions would require more detailed embodied simulation of motor actions than comprehension of familiar expressions. Results supported this hypothesis: degree of activation of primary hand motor areas was inversely related to metaphor familiarity (i.e., less familiar metaphors led to greater activation of motor areas). Desai et al. interpreted this finding as supporting a gradual abstraction account, in which relatively detailed simulations are used when understanding unfamiliar metaphors, with these simulations gradually becoming less detailed and engaging only secondary motor regions (e.g. the aIPL) as metaphors become more familiar. Overall, Desai et al. supported the idea that embodied cognition plays a role in processing sensorimotor metaphors and suggested that metaphor familiarity influences the nature of that role.

Most recently, Reilly et al. (2019) used single-pulse TMS to disrupt neural activity in hand areas of participants' left primary motor cortex during stimulus presentation. Participants were presented with four types of sentence stimuli: literal non-action ("The country wanted the plan for a nuclear program"), literal action ("The craftsman lifted the pebble from the ground"), metaphoric action ("The discovery lifted the nation out of poverty"), and nonsense ("All the dom occeniow more lecese"). Participants were instructed to press a response key to indicate whether each presented sentence made sense. The effects of single-pulse TMS stimulation are temporally specific with no carryover effects, which allows researchers to administer TMS stimulation to each participant on half of the trials, with the other half presented without stimulation.

Reilly et al. observed that TMS stimulation impaired processing of both literal action and metaphoric action sentences, as indexed by longer decision times on trials with stimulation applied. By contrast, decision times on literal non-action sentences were not affected by TMS. This pattern establishes a causal link, showing that the motor cortex is needed for fluent comprehension of motor metaphors. However, a limitation of Reilly et al. (2019) is that the researchers used only highly familiar motor metaphors, and thus were not able to investigate whether the impact of TMS changed as a function of metaphor familiarity.

Three neuroimaging studies have yielded results that are ambiguous or do not appear to support the ECSM hypothesis. In the earliest of these, Aziz-Zadeh et al. (2006) visually presented participants with linguistic and video stimuli while recording neural activity through fMRI. The linguistic stimuli consisted of short metaphoric and literal phrases that referenced motor actions related to the mouth (e.g. *chewing)*, hands (e.g. *grasping)*, and feet (e.g. *kicking).* Stimuli were presented such that each participant saw both literal and metaphoric phrases referencing each type of motor action: mouth (e.g. *chewing the banana* – literal; *chewing over the details* – metaphoric), hand (e.g. *grasping the pen* – literal; *grasping the idea* – metaphoric), and foot (e.g. *running across the field* – literal; *time is running* – metaphoric). A total of 30 sentences were presented across these conditions, each for 1.5 seconds, and participants (N = 12) were instructed to read each sentence. Following presentation of the phrase stimuli, participants also viewed short videos in which actors performed motor actions with their mouth (e.g., a mouth biting into a peach), hands (e.g., a hand grasping a pen) or feet (e.g., a foot pressing on a piano pedal). Each video lasted 1.5 seconds, matching the sentence presentation interval.

Aziz-Zadeh et al. (2006) measured activation in areas of the ventral premotor cortex (vPMC) corresponding to mouth, hand, and foot motor activity based on established activation mappings (Buccino et al., 2001; Wheaton et al., 2004). Results indicated activation in corresponding areas of the vPMC when participants watched videos and read sentences related to mouth, hand, and foot actions. However, metaphoric phrases did not elicit vPMC activity. These results add to the established conclusions that observing (Buccino et al., 2001; Grafton, 2009) and reading literal descriptions (Hauk et al., 2004; Tettamanti et al., 2005) of motor actions engages embodied motor simulation, but appear to cast doubt on the idea that sensorimotor metaphors similarly engage embodied simulation. To explain this result, Aziz-Zadeh et al. (2006) suggested that metaphors may activate a different neural network once they are learned compared to when they are originally encountered, with the effect that more familiar metaphors no longer activate motor areas. As such, Aziz-Zadeh et al. suggested that the (informally assessed) high familiarity of their metaphor stimuli may have affected their results. This suggestion that the high familiarity of metaphoric stimuli may account for the lack of neural motor activation predates, and may have influenced, Desai et al.'s (2011) familiarity hypothesis.

In a German language fMRI study, Rüschemeyer et al. (2007) investigated whether abstract-meaning verbs would be processed differently depending on whether they were built on word stems related to motor actions or stems with abstract meaning. For instance, the abstract-meaning verb *begriefen,* which means *to comprehend,* is based on a motor stem *(griefen, to grasp)*, whereas the similar abstract-meaning verb *bedenken*, which means *to consider*, is built on an abstract stem (*denken*, to think). Despite being a single word, a German verb like *begreifen* is analogous to an English metaphor like *she grasped the idea* because a physical action (*greifen*, to grasp) is used to evoke the abstract idea of comprehension. Participants (N=20) were presented with the words displayed one at a time on a monitor inside an fMRI scanner. Forty-six verbs were presented for 700 ms each, with 23 being based on abstract stems (e.g. *bedenken*) and 23 being based on motor stems (*e.g. begriefen*). Results indicated that motor verbs like *griefen* significantly activated areas of the primary motor cortex, whereas abstract verbs like *denken* did not. However, abstract-meaning composite verbs did not activate neural motor areas even when they were built on motor stems (e.g. *begriefen*). Because this suggests that embodied simulation was not involved in comprehending verbs that convey abstract concepts (like comprehension) by relating them to physical actions (like grasping), this result does not support the ECSM hypothesis.

In another fMRI study, Raposo et al. (2009) presented participants with hand/arm (e.g. *grab*) or foot/leg (e.g. *kick*) action words presented either in isolation, in literal sentences (e.g., *After six minutes, the new recruit kicked the ball*), or in metaphoric sentences (e.g., *The job offer was a great chance so Claire grabbed it*). Participants (N=22) listened to voice recordings of 56 literal and 56 metaphoric sentences while their neural activity was recorded. Following presentation of the sentence stimuli, all participants performed a motor localizer task in which they were instructed to move their index fingers and each foot, allowing researches to precisely localize each participants' neural activation associated with actual foot and hand movements. Recordings of action words in isolation were presented in a separate session.

Raposo et al. (2009) found significant activation in areas of the motor and premotor cortices associated with hand and foot motion in response to action words presented in isolation and literal sentences containing action words. Activation observed for these stimuli significantly overlapped with activation observed for actual foot and hand motions in the motor localizer task. However, metaphoric sentences containing action words did not significantly activate hand- and foot-associated areas of the motor and premotor cortices. This result fails to support the idea that embodied simulations are involved in processing sensorimotor metaphors. In addition, the fact that action words in sensorimotor metaphors did not activate the motor or premotor cortices suggests that embodied simulation is context-dependent rather than automatic in response to action words.

Clearly, support is mixed for the idea that embodied simulations are involved in processing of motor metaphors. Methodological differences among studies on this topic might partially account for these conflicting findings. However, the results of Desai et al (2011) might provide another plausible explanation, which is that embodied simulation becomes weaker as familiarity increases. This conclusion is important for two reasons. First, it fits with findings from prior research that suggest that comprehension of less familiar metaphors requires analysis and consideration of the metaphoric mapping and particularly the source domain, whereas comprehension of highly familiar metaphors is automatic and does not require consideration of this mapping (Bowdle & Gentner, 2005). Second, the idea that neural motor activity is inversely related to metaphor familiarity may account for several null results in studies of embodied cognition in motor metaphor processing, and thus explain the inconsistent findings in this body of work.

How does the idea that detailed embodied simulations are engaged only for less familiar metaphors fit with earlier research on conceptual access in metaphor processing? As proposed in the ECSM hypothesis (Gibbs, 2006; Ritchie, 2008), when sensorimotor metaphors (e.g., *grasp the idea*) are read, embodied sensory or motor simulations of the metaphoric source domain (e.g., simulation of physical grasping) are activated in order to arrive at the target domain (e.g., the concept of understanding), thus facilitating comprehension. As others have noted (e.g., Lacey et al., 2012), this process seems to imply that the conceptual mapping underlying the metaphoric expression is accessed during comprehension. How does this relate to metaphor familiarity? As discussed earlier, some research has indicated that highly familiar metaphoric expressions may become lexicalized and have a separately stored meaning that is accessed directly during comprehension, eliminating the need to access the underlying associative mapping (e.g., Keysar & Bly, 1999; Keysar et al., 2000). Similarly, the Career of Metaphor model (Bowdle & Gentner, 2005) which is one of the dominant models of metaphor processing, specifies that highly conventional metaphors are understood automatically, an idea that has been supported by a recent study examining the automaticity of metaphor and simile processing (Pambuccian & Raney, 2020). Accordingly, in motor metaphors, automatic retrieval of an existing meaning may not require embodied motor simulation. This is consistent with the idea that embodied simulations are not performed when processing highly familiar sensorimotor metaphors (as their meanings are accessed directly). In contrast, sensory simulations are activated to facilitate comprehension of less familiar metaphors (for which comprehension is not automatic and requires consideration of the metaphoric mapping; Bowdle & Gentner, 2005).

The possibility that embodied simulation is involved only when processing unfamiliar metaphors also provides a plausible explanation for why several studies found no evidence of embodied simulation in response to metaphors. Aside from Desai et al. (2011), the studies reviewed in this paper used only relatively familiar metaphoric expressions as stimuli. Thus, the fact that Rüschemeyer et al. (2007), Raposo et al. (2009), and Desai et al. (2013) did not observe significant neural activity indicative of embodied simulation may be attributed in part to using only highly familiar metaphor stimuli. In particular, in Rüschemeyer et al. (2007), the fact that the German metaphors presented were single words may have made them even more familiar and more likely to be treated as lexicalized items. Similarly, observations of significantly weaker neural motor activity for metaphors than for literal sentences (e.g., Lauro, 2013) may be related to the use of predominantly high-familiarity metaphors.

Reilly et al. (2019) were able to disrupt processing using TMS pulses. Their findings are important because they provide strong evidence for a causal role of the motor cortex in motor metaphor processing. Reilly et al.'s findings support the conclusion that the motor cortical activation observed in response to motor metaphors in prior research reflected embodied simulation processes that play an important, facilitatory role in motor metaphor processing. The alternative explanation – that observed neural motor activity is epiphenomenal and unrelated to the motor metaphor comprehension processes – is incongruent with the finding that motor cortical activity is necessary for fluent motor metaphor comprehension.

F. **Background and Current Study**

Two general possibilities arise from previous research on embodied cognition in motor metaphor processing. The first is that, in a motor metaphor like *she grasped the idea*, the figurative meaning of the word *grasp* is grounded in the literal meaning. Accordingly, understanding the figurative meaning will thus require, or at least be facilitated by, embodied simulation of physical grasping. The second possibility is that the figurative meaning of the word *grasp* is a separate, unrelated meaning from the literal meaning. If this is correct, processing the motor metaphor should not engage embodied simulation of physical grasping, as the figurative meaning is separate from the literal meaning. Although some studies have yielded results supporting the first possibility, this support is not unanimous.

The present study aimed to (1) assess the role of motor cortical activity during processing of motor metaphors; and by extension (2), to assess whether the figurative meanings of action words in motor metaphors are grounded in the literal meanings, or are separate and unrelated meanings. To paint a clearer picture of motor metaphor processing, motor cortical activity was assessed during processing of low- and high-familiarity metaphors. To my knowledge, this is the first study on this question since Desai et al. (2011) to present stimuli across a range of familiarity, and to thus provide insights as to whether the inverse relationship between embodied simulation and metaphor familiarity observed by Desai et al. (2011) is replicable.

This study used transcranial direct current stimulation (tDCS) to directly manipulate cortical activity while metaphors were processed. To my knowledge, tDCS has never been used to study embodied cognition in metaphor processing. Similar to TMS, tDCS is a neurostimulation technique that can interfere with or enhance neural signals in specific regions of the brain, thereby impairing or facilitating specific, localized functions. However, tDCS and TMS affect brain function through different mechanisms. Whereas TMS uses a magnetic field to induce electromagnetic induction in a localized brain area, tDCS passes a very small electrical current across the cortex via electrodes placed on the scalp. In tDCS, Positive (anodal) current temporarily facilitates neural activity in regions below the target electrode, and negative (cathodal) current inhibits neural activity (Thair et al., 2017).

Given the similarities between the two methodologies, Reilly et al.'s (2019) TMS study is a logical model for a tDCS study of embodied cognition in metaphor processing. Specifically, tDCS can be used to stimulate the motor cortex while the participant processes motor metaphors. As such, a tDCS manipulation has the potential to yield valuable information. A potential advantage of using tDCS rather that TMS is that tDCS is a significantly less expensive and less invasive technique, allowing for the collection of a larger number of participants given similar financial constraints.

In the present study, I used tDCS to investigate the role of embodied cognition in motor metaphor processing using an experimental design based on Reilly et al.'s (2019) TMS study. Rather than TMS, I used anodal tDCS to electrically stimulate the and enhance activity in the motor cortex while participants read sentence stimuli. To assess the role of embodied motor simulation in motor metaphor processing, I examined whether tDCS stimulation differentially impacted motor metaphor processing compared to processing of literal sentences. Four types of sentence stimuli were presented: literal sentences containing a motor word, literal sentences containing no motor word, figurative sentences containing a motor metaphor, and nonsense sentences. All action words pertained to hand- or arm-related actions. As in Reilly et al., participants were asked to indicate, as quickly and accurately as possible, whether each sentence "makes sense." However, unlike Reilly et al., I manipulated the familiarity of the metaphor stimuli to assess whether the impact of tDCS varied as a function of metaphor familiarity. This allowed me to evaluate the hypothesis that embodied cognition is differentially engaged depending on metaphor familiarity, as found by Desai et al. (2011).

Compared to single-pulse TMS, the effect of tDCS on neural function is less temporally specific. As such, I measured the impact of tDCS over the course of an entire experimental session (rather than on a per-trial basis). Each participant was randomly assigned to receive either active anodal stimulation or no stimulation. Participants in the active stimulation condition received 2.0 milliamps of continuous direct current, which is sufficient to influence motor cortical activity. In both conditions, participants were instructed to make sensibility judgments on the presented sentences (as in Reilly et al, 2019) .

Sentences (aside from nonsense sentences) were drawn from the stimuli used by Desai et al. (2011), which were normed on familiarity. Unlike in Reilly et al's (2019) TMS study, participants were presented with metaphor stimuli spanning a wide range of familiarity. In particular, I assessed whether tDCS stimulation differentially facilitated metaphor processing as a function of familiarity. As such, the proposed study directly tested the familiarity hypothesis proposed by Desai et al. (2011) – that embodied cognitive processes are more important to comprehension of unfamiliar than familiar motor metaphors. Finding that tDCS stimulation facilitates processing of unfamiliar motor metaphors to a greater degree than familiar motor metaphors would support this hypothesis. Moreover, this result would provide causal evidence of the facilitatory role of embodied cognition in motor metaphor processing, which was not possible in Desai et al. (2011) study.

Sensibility judgment response times were compared between the no stimulation and active stimulation conditions for literal motor, literal non-motor, motor metaphor, and nonsense sentences. The following hypotheses were tested:

1. Neurostimulation (anodal tDCS) will differentially speed response times as a function of sentence type (Sentence Type X Stimulation Condition interaction). Relative to no stimulation, active stimulation will have the greatest facilitatory effect (speed-up) on response times for literal motor sentences, followed by motor metaphors. Stimulation is not expected to facilitate response times for literal non-motor or nonsense sentences. See Figure 1 (Appendix A) for a graphical depiction of this pattern of results).
2. Within motor metaphors, neurostimulation will differentially speed response times as a function of metaphor familiarity. Specifically, neurostimulation is expected to facilitate (speed up) comprehension of unfamiliar metaphors more than comprehension of familiar metaphors. See Figures 2 and 3 (Appendix A) for a graphical depiction of this pattern of results.

II. METHOD

A. **Participants**

Fifty five undergraduate students from the University of Illinois at Chicago (UIC) psychology subject pool were recruited to participate in the study in exchange for course credit. To assess language backgrounds and vocabulary knowledge among participants, all participants completed a language history questionnaire and vocabulary quiz (described below). Participants were required to be proficient English speakers, which was defined as attending English-speaking schools for at least 10 years, self-rating their speaking and comprehension of English as a 9 or 10 on a 10-point scale, and scoring at least 5 out of 15 on the vocabulary test. Participants were prescreened to be right-handed.

B. **Materials**

A total of 60 sentences were presented, across four categories of sentences: literal motor sentences, motor metaphor sentences, literal non-motor sentences, and nonsense sentences. Literal motor sentences are sentences in which a motor action word is used literally (e.g., *the architect grasped the pen*). Motor metaphor sentences are sentences in which a motor action word is used figuratively (e.g., *the student grasped the idea*). Literal non-motor sentences are sentences that are synonymous with motor metaphors but expressed literally, without the use of any motor words (e.g., *the student understood the idea*). Nonsense sentences are sentences that are semantically nonviable. Of the nonsense sentences, half included an action word (e.g., *the man punched the need*) and half did not include an action word (e.g., *the worker browsed the ball*).

Literal motor sentences, motor metaphor sentences, and literal non-motor sentences were drawn from stimuli used by Desai et al. (2011), who collected familiarity ratings for the motor metaphor stimuli. Motor metaphors were selected to span a wide range of familiarity, with half of the metaphors selected from lowest quartile of familiarity ratings and half selected from the top quartile. Nonsense sentences were created to match the structure of the literal and metaphor sentence stimuli.

Sentences were presented in a pseudorandomized order, manipulated such that no one type of sentence (Literal Motor, Literal Non-Motor, Motor Metaphor, and Nonsense) appeared more than three times consecutively. Sentences were displayed on a 15-inch monitor in 12pt black font on a white background, with participants maintaining a viewing distance of approximately 50 centimeters.

An English Vocabulary quiz developed by Raney was used to measure English word knowledge (see Appendix B). The test consists of 15 multiple-choice items for which the participant is instructed to choose the best answer among five alternatives. A version of this vocabulary test has been used in prior studies at UIC (Minkoff & Raney, 2000; Therriault & Raney, 2007), and has been found to be correlated with reading comprehension skill (r = 0.40 to 0.52). The average score for UIC undergraduates participating in research studies is approximately 8 (the test is designed to be difficult). The vocabulary test was administered to ensure basic knowledge of English vocabulary.

The Language History Questionnaire consists of several questions asking participants to list which languages they know, which language they learned first, and to rate their proficiency in speaking, comprehending, and reading each of the languages they know. The Language History Questionnaire is provided in Appendix B. Collecting language history allowed me to more completely describe the participant population, which could facilitate potential future comparisons to other studies conducted on less linguistically diverse samples.

C. **Procedure**

Participants performed the experiment in a quiet room in the Behavioral Sciences Building (BSB). One or two participants were tested per session. Participants were randomly assigned to either the no stimulation condition or active tDCS stimulation condition. Prior to beginning the experiment, participants were asked to read and sign an informed consent form that outlined the experimental procedures. For participants assigned to the active stimulation condition, the researcher also explained transcranial direct current stimulation prior to obtaining consent. Participants in the active stimulation condition then filled out a tDCS screening questionnaire, which asked whether participants met any criteria for which tDCS may be contraindicated, such as whether the participant has any open head wounds. The tDCS screening questionnaire is provided in Appendix C. Any participant who responded “yes” to any screening question was instead assigned to the no stimulation condition.

Participants in the active stimulation condition who meet the screening requirements were next prepared for tDCS. The tDCS procedures followed the recommendations made by Fregni et al. (2015). First, the participant’s head was measured to determine the location of tDCS electrode placement. The electrode sponge was placed approximately 5cm to the left of the vertex (top center of head) to target the hand area of the left primary motor cortex. Second, the area of attachment was swabbed with an alcohol pad. Third, the electrode sponge was placed on the scalp and held in position with a headband. The electrode sponge was soaked in saline solution to ensure electrical contact with the scalp. Fourth, a second (reference) electrode was placed on the right arm just above the elbow.

In the active stimulation condition, participants experienced 2.0 milliamps of anodal continuous direct current throughout the experimental tasks. When starting stimulation, participants were asked to rate their discomfort on a scale from 1 (Very Comfortable) to 10 (Very Uncomfortable). In addition, the participant was asked to tell the experimenter if they experienced significant discomfort at any point during the experiment, at which the stimulation portion of the experiment would be discontinued and the tDCS electrodes removed.

The primary experimental task was a sensibility judgment task. In both the active stimulation and no stimulation conditions, participants were presented with the sentence stimuli one at a time and instructed to press one of two response buttons to indicate whether the sentence "makes sense" or "does not make sense." Participants were instructed to perform the button presses using their left hands so as to ensure that button pressing was not affected by the tDCS stimulation of the left motor cortex (which controls the right hand).

After completing the sensibility judgment task, participants completed the Language History Questionnaire and the Vocabulary Test. The duration of a single experimental session did not exceed 30 minutes.

D. Apparatus

Neurostimulation was administered using The Brain Stimulator v3.0 tDCS device (https://thebrainstimulator.net). Electrodes were applied using 2x2 inch saline-soaked sponges.

III. RESULTS

The first hypothesis predicted a Sentence Type X Stimulation Condition interaction: active stimulation condition participants would have faster response times than no stimulation condition participants for motor literal and motor metaphor sentences, but response times would not differ between the two conditions for literal non-motor and nonsense sentences. To test this hypothesis, response time data from the sensibility judgment task were analyzed using a linear mixed-effects model. Log-transformed response times were analyzed as a function of stimulation condition (none or active), sentence type (Literal Motor, Literal Non-Motor, Motor Metaphor, and Nonsense), and their interaction as fixed effects. A maximal random effects structure (Barr et al., 2013) was initially tested, which was simplified until the model converged. This resulted in a final model with random intercepts and for each participant and each item, which was run in R (lme4 package) using the following code: lmer(logRT ~ 1 + StimulationType * SentenceType + (1|Subject) + (1|Item)). Both the participant and item intercepts were significant (p < .001). Overall, the fixed effects alone explained 9.9% of variance in comprehension times ($R^2_{marginal} = 0.099$), while the fixed and random effects combined explained 24.1% ($R^2_{conditional} = 0.241$).

The final model revealed a main effect of sentence type, $F(3, 40) = 29.23$, $p < .001$, $R^2_{marginal} = 0.089$, no main effect of stimulation condition, $F(1, 55) = 2.19$, $p = .144$, $R^2_{marginal} = 0.01$, and a stimulation condition X sentence type interaction, $F(3, 1850) = 3.23$, $p = .022$, $R^2_{marginal} = 0.09$. Post hoc tests (Bonferroni corrected pairwise comparisons) were conducted to follow up the main effect of sentence type, revealing that response times for literal motor sentences (M = 1806, SD = 770) were significantly faster than for any of the other three sentence types: motor metaphors (M = 2381, SD = 778), $t(47) = 8.76$, $p < .001$, literal non-motor sentences (*M* = 2198, *SD* = 836), $t(47) = 5.93$, $p < .001$, and nonsense sentences (*M* = 2240, *SD* = 920), $t(47) = 6.66$, $p < .001$. There were no significant differences in response times between motor metaphors and nonliteral motor sentences, $t(47) = 2.66$, $p = .06$, between motor metaphors and nonsense sentences, $t(47) = 2.60$, $p = .08$, or between literal non-motor and nonsense sentences, $t(47) = 0.25$, $p = 1.00$.

Given the hypothesis that the impact of stimulation would differ by sentence type, planned comparisons were conducted to follow up the stimulation condition X sentence type interaction, testing the simple effect of stimulation condition in each of the four sentence types. Results indicate that stimulation condition response times were significantly faster than control response times for literal motor sentences, $F(1, 91) = 5.94$, $p = .02$, and for motor metaphors, $F(1, 164) = 4.15$, $p = .04$. There was no significant difference in response times between the two stimulation conditions for literal non-motor sentences, $F(1, 166) = 0.08$, $p = .78$, or for nonsense sentences, $F(1, 91) = 0.54$, $p = .46$.

The second hypothesis predicted an interaction within metaphor stimuli – the difference between active stimulation and no stimulation condition response times would be larger for unfamiliar than familiar metaphors (with active stimulation response times being faster in both cases). To test this hypothesis, the metaphor sentence type in the previous analysis was analyzed as two categories: familiar metaphors and unfamiliar metaphors. A linear mixed-effects model was used to analyze sensibility judgment task response times as a function of stimulation condition (none or active), sentence type (familiar motor metaphor, unfamiliar motor metaphor), and their interaction as fixed effects. A maximal random effects structure was initially tested, which was simplified until the model converged. This resulted in a final model with random intercepts and for each participant and each item, which was run in R (package: lme4) using the following code: lmer(logRT ~ 1 + StimulationType * DetTrialType + (1|Subject) + (1|Item)). Both the subject and item intercepts were significant (p < .001). Overall, the fixed effects alone explained 10.5% of variance in comprehension times ($R^2_{marginal} = 0.105$), while the fixed and random effects combined explained 24.1% ($R^2_{conditional} = 0.241$).

There was a main effect of sentence type, F(1, 45) = 27.47, p < .001, $R^2_{marginal} = 0.095$, no main effect of stimulation condition, F(1, 60) = 2.83, p = .097, $R^2_{marginal} = 0.01$, and a Stimulation Condition X Sentence Type interaction, F(4, 1850) = 2.49, p =.041, $R^2_{marginal} = 0.09$. To avoid redundancy with the previous analysis, the main effect of sentence type was not followed up.

I hypothesized that the difference between no stimulation and active stimulation response times would be greater in unfamiliar than familiar metaphors. As such, planned comparisons were conducted to test the simple effect of stimulation condition in unfamiliar metaphors and in familiar metaphors. Results indicated that response times in the active stimulation condition were significantly faster than those in the no stimulation condition for unfamiliar metaphors, F(1, 359) = 3.90, p = .049, but not for familiar metaphors, F(1, 45) = 1.74, p = .188.

IV. DISCUSSION

Two major hypotheses were tested in this study. First, I predicted that neurostimulation (anodal tDCS) would differentially facilitate (speed up) response times as a function of sentence type. Specifically, neurostimulation was expected to facilitate processing of motor literal and motor metaphor sentences, but not literal non-motor or nonsense sentences. Second, I predicted that the facilitatory impact of neurostimulation would differ as a function of metaphor familiarity, with unfamiliar metaphors experiencing greater facilitation than familiar metaphors.

Both hypotheses were supported. The results support two conclusions. First, motor simulation is engaged when processing literal *and* figurative uses of motor words. Second, motor simulation is differentially engaged as a function of metaphor familiarity: relative to the no stimulation condition, facilitation was found for unfamiliar metaphors but not for familiar metaphors. In other words, the importance of motor simulation is greater for low- than for high-familiarity metaphors. This matches the hypothesis put forth by Desai et al. (2011), who proposed that detailed sensorimotor simulations are engaged for highly unfamiliar motor metaphors, with these simulations gradually becoming less detailed as metaphor familiarity increases.

These results have both methodological and conceptual implications. A major methodological implication concerns the use of tDCS to assess the involvement of motor simulation in language processing. In this study, tDCS neurostimulation facilitated processing of motor literal sentences like *the referee tossed the coin,* replicating effects found in prior fMRI studies in which neural activity indicative of motor simulation was observed in response to written descriptions of motor actions (e.g., Hauk et al., 2004). In addition, tDCS neurostimulation did *not* elicit facilitation for sentences with no coherent motor content (nonmotor literal and nonsense sentences). These results suggest that tDCS can be used in future experiments that aim to assess how modulation of motor cortical activity this modulation on language processing.

Beyond methodological implications, it is important to consider how this study informs our understanding of metaphor processing and embodied cognition. I will first address the implications for our understanding of metaphor processing, beginning with motor metaphors in particular. The results of this study indicate that embodied cognitive processes based in the motor cortex play an important role in processing of both literal *and* figurative uses of action words. This suggests that the literal meaning of the motor words is accessed during processing of motor metaphors in a manner that facilitates comprehension of the expression's figurative meaning rather than competing with the figurative meaning. This supports the idea that the figurative meanings of motor metaphors are grounded in, and derived from, the literal meanings (Reilly et al., 2019).

Because the results indicate that an embodied processing pathway (motor simulation) contributes to motor metaphor comprehension, existing models of metaphor comprehension may need to be revised to describe such a pathway. In particular, models of metaphor comprehension should seek to make testable predictions about the precise role of an embodied pathway in metaphor comprehension. For instance, is this pathway relevant only to metaphors with explicit sensory or motor source domains, or is it also active when processing other types of figurative language? Aside from explicit sensory/motor metaphors, some emotion-conveying figurative expressions that appear to indirectly reference bodily sensations (e.g., *my blood is boiling*) may engage embodied processing pathways. In addition, if embodied pathways are used when processing some types of metaphoric expression, it is important to understand how these pathways interact with non-embodied processing pathways, and how this relationship changes with shifts in metaphor familiarity.

Although current models of metaphor processing lack any description of embodied cognitive processes contributing to metaphor comprehension, they are not necessarily incompatible with the results of the present study. The Career of Metaphor (COM) model (Bowdle & Gentner, 2005), in particular, parallels the results of the present study in an interesting way. In the Career of Metaphor model, highly conventional metaphors are understood through automatic processes, whereas metaphors below this conventionality threshold threshold rely on effortful, controlled comprehension processes (though not the same as familiarity, conventionality is a closely related measure: for a discussion, see Damerall & Kellogg, 2016). This shift from controlled to automatic processing mirrors the shift from embodied to nonembodied (or more-embodied to less-embodied) processing proposed by Desai et al. (2011) and supported by the results of the present study. As such, the COM model could easily be revised to account for embodied cognitive processes in metaphor comprehension. Such a revision could describe unfamiliar metaphor comprehension as relying on a diverse range of processes that may include both embodied and nonembodied cognitive processes, depending on the type of metaphor encountered. By contrast, comprehension of highly familiar metaphors may rely on a less diverse set of processes, with all highly familiar metaphors being processed via nonembodied automatic processes regardless of whether the metaphor contains motor words.

The comparison to the COM model also presents a conceptual question regarding the nature of the familiarity-moderated shift from more-embodied to less-embodied processing of motor metaphors. One possibility is that there is a continuous relationship between metaphor familiarity and embodied cognition. In this view, processing of sensorimotor metaphors may involve detailed embodied simulations that engage primary neural motor or sensory areas, with these simulations gradually becoming less detailed and engaging only secondary motor or sensory areas as metaphors become more familiar. Desai et al. (2011) claimed empirical support for such a continuous relationship based on their observation that unfamiliar metaphors activated both primary and secondary neural motor regions, whereas more familiar metaphors activated only secondary neural motor regions. A second possibility is that there is a discrete relationship in which unfamiliar sensorimotor metaphors engage embodied simulation whereas familiar sensorimotor metaphors do not. This possibility is not entirely incompatible with the continuous relationship proposed by Desai et al. (2011; 2013). It is possible that the relationship proposed by Desai et al. holds true for metaphors below a certain familiarity threshold, but that metaphors above this threshold, representing the highest-familiarity metaphors, are processed without the involvement of any embodied simulation. This hybrid discrete/continuous model parallels the COM model, which specifies both a continuous relationship (within less familiar metaphors) and a discrete relationship (between less familiar and highly familiar metaphors) between conventionality and processing automaticity.

It is also worth considering whether the "shift" from embodied to nonembodied processes refers to a categorical switch between the two types of processing. One possibility is that the "shift" is indeed a categorical switch from one type of processing to anther – that comprehension of any given motor metaphor activates either exclusively embodied or exclusively nonembodied cognitive processes depending on the metaphor's familiarity. However, another possibility is that both embodied and nonembodied processes operate in parallel for all motor metaphors. If embodied and nonembodied processes operate in parallel, the familiarity of a motor metaphor would determine not the *type* of processing used for comprehension, but rather which type of processing (embodied or nonembodied) is able to access the meaning *first*. In this kind of "horse race" model (e.g., Paap & Noel, 1991), embodied cognitive processes win the race when motor metaphors are unfamiliar, whereas nonembodied processes win the race when motor metaphors are familiar. In this account, the threshold at which processing "shifts" from embodied to nonembodied cognitive processes is better understood as the threshold at which nonembodied processes begin to win the horse race (access the meaning first) against embodied processes.

Future research could differentiate among these possibilities by presenting sensorimotor metaphors that span a wider range of familiarity, including metaphors at the very highest end of the familiarity spectrum (which were not presented by Desai et al., 2011). Including a wider range of familiarity would allow greater granularity in determining the familiarity threshold at which motor stimulation no longer facilitates motor metaphor processing. In addition, future studies could probe the opposite extreme of familiarity by examining whether processing novel sensorimotor metaphors leads to the strongest activation of neural sensory/motor areas. Novel sensorimotor metaphors could be created based on existing metaphoric mappings. For instance, a novel metaphor like *he put his hands around the idea* could be constructed based on the mapping UNDERSTANDING IS PHYSICAL HOLDING, which also underlies the more familiar metaphor *he grasped the idea.*

A more speculative metaphor-related implication is that if embodied cognitive processes are involved in processing certain metaphors, this could contribute to our subjective impression of metaphoric expression. Metaphoric expression, particularly metaphoric expression of emotions, is subjectively experienced as more vivid and evocative than literal expression (Ortony, 1975; Ortony & Fainsilber, 1987). Metaphor familiarity plays a role in this effect: individuals produce more novel metaphors when describing intense emotions than mild emotions, and also produce more novel metaphors when describing their own emotions relative to the emotions of others (Williams-Whitney et al., 1992). Embodied cognitive processes like sensorimotor simulation could help explain why we find some metaphors particularly vivid, or why we reach for metaphoric expressions rather than literal ones. For instance, we might more vividly relate to a friend's breakthrough if they say *I think I've finally grasped the idea!* than if they say *I think I've finally understood the idea!* Perhaps this is because the first expression causes us to mentally simulate the physical act of grasping, which vividly evokes the feeling of attainment we experience upon finally understanding a difficult concept.

This study's results may also hold implications for embodied cognition. The mappings that underlie sensory and motor metaphors – like the mapping between physical holding and understanding – are examples of potential pathways between embodied experiences and abstract concepts. The finding that motor simulation plays a role in processing motor metaphors demonstrates this pathway in action. Because such pathways could theoretically be used to explain a broader range of abstract cognition, this is of interest to models that aim to explain abstract cognition as grounded in embodied cognitive processes (e.g., Casasanto 2008; 2009).

Another potential implication for embodied cognition relates to the apparent shift in the importance of embodied cognitive processes as metaphor familiarity changed. Specifically, stimulating the motor cortex significantly facilitated comprehension of unfamiliar but not familiar metaphors. Although familiar metaphors appear to be processed faster in the stimulation condition relative to the no stimulation condition, this was not a statistically reliable difference. This pattern of results suggests that sensorimotor simulations plays a larger role in unfamiliar metaphor processing. Given this apparent weakening or extinction of the embodied processing pathway as familiarity increases, an intriguing possibility is that this effect is not specific to motor metaphors. It is possible that many abstract concepts are initially learned and accessed through embodied pathways that link the concept to a concrete experiential domain. As the concept becomes more familiar, (potentially more efficient) non-embodied pathways are gradually built to allow direct access to the concept, weakening and eventually extinguishing the embodied pathways.

The results of this study support several ideas and methodological directions for future research. First, the results indicated that sensorimotor simulation plays a larger role in the processing of unfamiliar metaphors than familiar metaphors. However, a remaining question is whether the shift is gradual (more detailed to less detailed simulations as familiarity increases, as proposed by Desai et al., 2011) or categorical, with no engagement of motor simulation above a certain familiarity threshold (mirroring the shift from controlled to automatic processes as familiarity increases proposed by Bowdle & Gentner, 2005). To better understand whether familiarity functions as a continuous or categorical mediator, future work should manipulate familiarity as a continuous variable. This can be done by adding moderately-familiar metaphors to the set of stimuli.

In addition, future work using the tDCS methodology should consider using a “sham stimulation” condition as the control condition. In the “sham stimulation” condition, the participant have the tDCS electrodes attached exactly as done in the active stimulation condition, but the electrodes will either transmit no current or a much weaker current that does not influence cognitive activity. As a comparison condition, the benefit of a sham condition is that any expectancy effects induced by the mere presence of the tDCS electrodes are equalized between the two conditions, ensuring that any differences between conditions are attributable only to tDCS neuromodulation.

Finally, it is important to acknowledge that aside from the factors assessed in this study, word-level characteristics like word frequency also play a role in the way a figurative or literal expression is processed. In the present study, a majority of the stimuli presented were drawn from the normed stimuli used by Desai et al. (2011). These stimuli were not matched for word frequency across conditions (i.e., the average word frequency of literal motor and literal nonmotor stimuli were not necessarily equivalent). Because the present study aims to compare how stimuli are processed with and without motor cortical stimulation, differences in average word frequency across the different types of stimuli are not a major concern.

In the present study, I found that stimulating the motor cortex facilitated processing of both literal and figurative uses of motor action words. In figurative motor expressions, this facilitation was moderated by the expression's familiarity: unfamiliar expressions saw greater facilitation than familiar expressions. Taken together with the results of previous studies (e.g., Desai et al., 2011; Reilly et al., 2019), these results suggest that embodied simulation of motor actions is part of the comprehension process for motor metaphors, particularly when the metaphor is unfamiliar. These results also suggest that the figurative meanings of motor words are grounded in the literal meaning not just etymologically, but actively during processing, such that simulating the literal meaning facilitates access to the literal meaning. Motor metaphors like *grab your chance* or *grasp the idea* are ubiquitous, and the results of this study contribute a more complete understanding of how we process these commonly-used but rarely-studied expressions. In addition, the results of this study may inform how literal and figurative meanings of action words are modeled in artificial intelligence and natural language processing applications.

REFERENCES

Aziz-Zadeh, L., Wilson, S. M., Rizzolatti, G., & Iacoboni, M. (2006). Congruent embodied representations for visually presented actions and linguistic phrases describing actions. *Current biology*, *16*(18), 1818-1823.

Barsalou, L. W. (1999). Perceptions of perceptual symbols. *Behavioral and brain sciences*, *22*(4), 637-660.

Bender, A., & Beller, S. (2011). Fingers as a tool for counting–naturally fixed or culturally flexible?. *Frontiers in psychology*, *2*, 256.

Boroditsky, L. (2000). Metaphoric structuring: Understanding time through spatial metaphors. *Cognition*, *75*(1), 1-28.

Boulenger, V., Shtyrov, Y., & Pulvermüller, F. (2012). When do you grasp the idea? MEG evidence for instantaneous idiom understanding. *Neuroimage*, *59*(4), 3502-3513.

Bowdle, B. F., & Gentner, D. (2005). The career of metaphor. *Psychological review*, *112*(1), 193.

Brooks, R. A. (1991). Intelligence without representation. *Artificial intelligence*, *47*(1-3), 139-159.

Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Fogassi, L., Gallese, V., ... & Freund, H. J. (2001). Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study. *European journal of neuroscience*, *13*(2), 400-404.

Cannon, W. B. (1927). The James-Lange theory of emotions: A critical examination and an alternative theory. *The American journal of psychology*, *39*(1/4), 106-124.

Casasanto, D. & Gijssels, T. (2015). What makes a metaphor an embodied metaphor?. *Linguistics Vanguard*, 1(1), pp. 327-337. Retrieved 20 Feb. 2018, from doi:10.1515/lingvan-2014-1015

Casasanto, D. (2008). similarity and Proximity: When Does Close in space mean Close in mind?. *Memory & Cognition*, *36*(6), 1047-1056.

Casasanto, D. (2009). Embodiment of abstract concepts: good and bad in right-and left-handers. *Journal of Experimental Psychology: General*, *138*(3), 351.

Casasanto, D. (2009). Embodiment of abstract concepts: good and bad in right-and left-handers. *Journal of Experimental Psychology: General*, *138*(3), 351.

Churchland, P. S., Ramachandran, V. S., & Sejnowski, T. J. (1994). A critique of pure vision. *Large-scale neuronal theories of the brain*, 23-60.

Dalgleish, T. (2004). The emotional brain. *Nature Reviews Neuroscience*, *5*(7), 583.

Damasio, A. R., Grabowski, T. J., Bechara, A., Damasio, H., Ponto, L. L., Parvizi, J., & Hichwa, R. D. (2000). Subcortical and cortical brain activity during the feeling of self-generated emotions. *Nature neuroscience*, *3*(10), 1049.

Damerall, A. W., & Kellogg, R. T. (2016). Familiarity and aptness in metaphor comprehension. *The American journal of psychology*, *129*(1), 49-64.

Davies, M. (1982). Idiom and metaphor. In *Proceedings of the Aristotelian Society* (Vol. 83, pp. 67-85). Aristotelian Society, Wiley.

Desai, R. H., Binder, J. R., Conant, L. L., Mano, Q. R., & Seidenberg, M. S. (2011). The neural career of sensory-motor metaphors. *Journal of cognitive neuroscience*, *23*(9), 2376-2386.

Ding, F. (2012). The interaction between metaphor and metonymy in emotion category. *Theory and Practice in Language Studies*, *2*(11), 2384.

Ding, F. (2015). Rethinking the cognitive study of metonymy. *Theory and Practice in Language Studies*, *5*(9), 1836.

Emanatian, M. (1995). Metaphor and the expression of emotion: The value of cross-cultural perspectives. *Metaphor and Symbol*, *10*(3), 163-182.

Fainsilber, L., & Ortony, A. (1987). Metaphorical uses of language in the expression of emotions. *Metaphor and Symbol*, *2*(4), 239-250.

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *The Quarterly Journal of Experimental Psychology*, *61*(6), 825-850.

Fussell, S. R. (1992). The use of metaphor in written descriptions of emotional states. *Unpublished manuscript, Carnegie Mellon University*, *418*.

Gallese, V. (2005). Embodied simulation: From neurons to phenomenal experience. *Phenomenology and the cognitive sciences*, *4*(1), 23-48.

Gallese, V., & Lakoff, G. (2005). The brain's concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive neuropsychology*, *22*(3-4), 455-479.

Gentner, D. (2001). Spatial metaphors in temporal reasoning. In *Spatial schemas and abstract thought* (pp. 203-222).

Gerrig, R. J., & Gibbs Jr, R. W. (1988). Beyond the lexicon: Creativity in language production. *Metaphor and Symbol*, *3*(3), 1-19.

Gibbs, R. W. (2006). Metaphor interpretation as embodied simulation. *Mind & Language*, *21*(3), 434-458.

Gibbs, R. W., Leggitt, J. S., & Turner, E. A. (2002). What's special about figurative language in emotional communication. *The verbal communication of emotions: Interdisciplinary perspectives*, 125-149.

Goschler, J. (2005). Embodiment and body metaphors. *Metaphorik. de*, *9*, 33-52.

Grafton, S. T. (2009). Embodied cognition and the simulation of action to understand others. *Annals of the New York Academy of Sciences*, *1156*(1), 97-117.

Hanks, P. (2004). The syntagmatics of metaphor and idiom. *International Journal of Lexicography*, *17*(3), 245-274.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron*, *41*(2), 301-307.

Heed, T., Beurze, S. M., Toni, I., Röder, B., & Medendorp, W. P. (2011). Functional rather than effector-specific organization of human posterior parietal cortex. *Journal of Neuroscience*, *31*(8), 3066-3076.

Jastorff, J., Begliomini, C., Fabbri-Destro, M., Rizzolatti, G., & Orban, G. A. (2010). Coding observed motor acts: different organizational principles in the parietal and premotor cortex of humans. *Journal of neurophysiology*, *104*(1), 128-140.

Kable, J. W., Kan, I. P., Wilson, A., Thompson-Schill, S. L., & Chatterjee, A. (2005). Conceptual representations of action in the lateral temporal cortex. *Journal of Cognitive Neuroscience*, *17*(12), 1855-1870.

Kable, J. W., Lease-Spellmeyer, J., & Chatterjee, A. (2002). Neural substrates of action event knowledge. *Journal of Cognitive Neuroscience*, *14*(5), 795-805.

Keysar, B., Shen, Y., Glucksberg, S., & Horton, W. S. (2000). Conventional language: How metaphorical is it?. *Journal of Memory and Language*, *43*(4), 576-593.

Klatzky, R. L., Lederman, S. J., & Reed, C. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *Journal of experimental psychology: general*, *116*(4), 356.

Kövecses, Z. (1986). *Metaphors of anger, pride and love: A lexical approach to the structure of concepts*. John Benjamins Publishing.

Kövecses, Z. (2000). Metaphor and emotion: Language, culture, and body in human feeling. *Cambriclge: Cambridge UP*.

Kövecses, Z. (2008). Conceptual metaphor theory: Some criticisms and alternative proposals. *Annual review of cognitive linguistics*, *6*(1), 168-184.

Lacey, Simon, Randall Stilla & K. Sathian. 2012. Metaphorically feeling: Comprehending textural metaphors activates somatosensory cortex. Brain and Language 120(3). 416–421.

Lachaud, C. M. (2013). Conceptual metaphors and embodied cognition: EEG coherence reveals brain activity differences between primary and complex conceptual metaphors during comprehension. *Cognitive Systems Research*, *22*, 12-26.

Lakoff, G. & Johnson, M. (1999): *Philosophy in the flesh. The embodied mind and its challenge to Western thought*, New York.

Lakoff, G. (2009). The Neural Theory of Metaphor. *The Cambridge Handbook of Metaphor and Thought*, 17.

Lakoff, G. (2014). Mapping the brain's metaphor circuitry: Metaphorical thought in everyday reason. *Frontiers in human neuroscience*, *8*, 958.

Lakoff, G. (2016). Language and emotion. *Emotion Review*, *8*(3), 269-273.

Lakoff, G., & Johnson, M. (1980). Metaphors We Live By. *ChicagoLondon: University of Chicago Press*.

Lauro, L. J. R., Mattavelli, G., Papagno, C., & Tettamanti, M. (2013). She runs, the road runs, my mind runs, bad blood runs between us: Literal and figurative motion verbs: An fMRI study. *NeuroImage*, *83*, 361-371.

Maalej, Z. (2004). Figurative language in anger expressions in Tunisian Arabic: An extended view of embodiment. *Metaphor and symbol*, *19*(1), 51-75.

Maalej, Z. A., & Yu, N. (Eds.). (2011). *Embodiment via body parts: Studies from various languages and cultures* (Vol. 31). John Benjamins Publishing.

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of physiology-Paris*, *102*(1-3), 59-70.

McGlone, F., & Reilly, D. (2010). The cutaneous sensory system. *Neuroscience & Biobehavioral Reviews*, *34*(2), 148-159.

Mischler III, J. J. (2013). *Metaphor across time and conceptual space: the interplay of embodiment and cultural models* (Vol. 3). John Benjamins Publishing.

Montoro, P. R., Contreras, M. J., Elosúa, M. R., & Marmolejo-Ramos, F. (2015). Cross-modal metaphorical mapping of spoken emotion words onto vertical space. *Frontiers in psychology*, *6*, 1205.

Narayanan, S. (1997). Karma: Knowledge-based action representations for metaphor and aspect. Unpublished doctoral dissertation, University of California, Berkeley.

Niedenthal, P. M., Barsalou, L. W., Winkielman, P., Krauth-Gruber, S., & Ric, F. (2005). Embodiment in attitudes, social perception, and emotion. *Personality and social psychology review*, *9*(3), 184-211.

Niedenthal, P. M., Mermillod, M., Maringer, M., & Hess, U. (2010). The Simulation of Smiles (SIMS) model: Embodied simulation and the meaning of facial expression. *Behavioral and brain sciences*, *33*(6), 417-433.

Niedenthal, P. M., Winkielman, P., Mondillon, L., & Vermeulen, N. (2009). Embodiment of emotion concepts. *Journal of personality and social psychology*, *96*(6), 1120.

Ortony, A. (1975). Why metaphors are necessary and not just nice. *Educational theory*, *25*(1), 45-53.

Ortony, A., & Fainsilber, L. (1987). The role of metaphors in descriptions of emotions. In *Proceedings of the 1987 workshop on Theoretical issues in natural language processing* (pp. 181-184). Association for Computational Linguistics.

Ortony, A., Reynolds, R. E., & Arter, J. A. (1978). Metaphor: Theoretical and empirical research. *Psychological Bulletin*, *85*(5), 919.

Paap, K. R., & Noel, R. W. (1991). Dual-route models of print to sound: Still a good horse race. *Psychological research*, *53*(1), 13-24.

Petersen, S. E., Fox, P. T., Posner, M. I., Mintun, M., & Raichle, M. E. (1988). Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature*, *331*(6157), 585.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience*, *6*(7), 576.

Pulvermüller, F. 2001. Brain reflections of words and their meaning. Trends Cogn Sci. 5:517--525.

Quadflieg, S., Etzel, J. A., Gazzola, V., Keysers, C., Schubert, T. W., Waiter, G. D., & Macrae, C. N. (2011). Puddles, parties, and professors: Linking word categorization to neural patterns of visuospatial coding. *Journal of Cognitive Neuroscience*, *23*(10), 2636-2649.

Radden, G. (2002). How metonymic are metaphors. *Metaphor and metonymy in comparison and contrast*, 407-434.

Radden, G. (2003). The metaphor TIME AS SPACE across languages. *Zeitschrift für Interkulturellen Fremdsprachenunterricht*, *8*(2).

Radua, J., Phillips, M. L., Russell, T., Lawrence, N., Marshall, N., Kalidindi, S., ... & David, A. S. (2010). Neural response to specific components of fearful faces in healthy and schizophrenic adults. *Neuroimage*, *49*(1), 939-946.

Raposo, A., Moss, H. E., Stamatakis, E. A., & Tyler, L. K. (2009). Modulation of motor and premotor cortices by actions, action words and action sentences. *Neuropsychologia*, *47*(2), 388-396.

Reilly, M., Howerton, O., & Desai, R. H. (2019). Time-course of motor involvement in literal and metaphoric action sentence processing: A TMS study. *Frontiers in psychology*, *10,* 371.

Richards, I. A. (1965). *The Philosophy of Rhetoric, A Galaxy Book* (p. 94). New York: Oxford University Press.

Ritchie, L. D. (2008). X IS A JOURNEY: Embodied simulation in metaphor interpretation. *Metaphor and Symbol*, *23*(3), 174-199.

Rüschemeyer, S. A., Brass, M., & Friederici, A. D. (2007). Comprehending prehending: neural correlates of processing verbs with motor stems. *Journal of cognitive neuroscience*, *19*(5), 855-865.

Saxbe, D. E., Yang, X. F., Borofsky, L. A., & Immordino-Yang, M. H. (2012). The embodiment of emotion: language use during the feeling of social emotions predicts cortical somatosensory activity. *Social cognitive and affective neuroscience*, *8*(7), 806-812.

Schachter, S., & Singer, J. (1962). Cognitive, social, and physiological determinants of emotional state. *Psychological review*, *69*(5), 379.

Semino, E. (2010). Descriptions of pain, metaphor, and embodied simulation. *Metaphor and Symbol*, *25*(4), 205-226.

Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. *Trends in cognitive sciences*, *17*(11), 565-573.

Sokol, R. I., & Strout, S. L. (2006). A complete theory of human emotion: The synthesis of language, body, culture and evolution in human feeling. *Culture & Psychology*, *12*(1), 115-123.

Solomon, R. C. (1984). Getting angry: The Jamesian theory of emotion in anthropology. *Culture theory: Essays on mind, self, and emotion*, 238-254.

Stilla, R., & Sathian, K. (2008). Selective visuo-haptic processing of shape and texture. *Human brain mapping*, *29*(10), 1123-1138.

Tabossi, P. (1988). Effects of context on the immediate interpretation of unambiguous words. *Journal of Experimental Psychology: Learning, Memory and, Cognition*, *14*, 153–162.

Tabossi, P., Colombo, L., & Job, R. (1987). Accessing lexical ambiguity: Effects of context and dominance. *Psychological Research*, *49*, 161–167.

Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo, P., ... & Perani, D. (2005). Listening to action-related sentences activates fronto-parietal motor circuits. *Journal of cognitive neuroscience*, *17*(2), 273-281.

Thagard, P., & Shelley, C. (2001). Emotional analogies and analogical inference. *The analogical mind: Perspectives from cognitive science*, 335-362.

van der Laan, L. N., De Ridder, D. T., Viergever, M. A., & Smeets, P. A. (2011). The first taste is always with the eyes: a meta-analysis on the neural correlates of processing visual food cues. *Neuroimage*, *55*(1), 296-303.

Veldhuizen, M. G., Albrecht, J., Zelano, C., Boesveldt, S., Breslin, P., & Lundström, J. N. (2011). Identification of human gustatory cortex by activation likelihood estimation. *Human brain mapping*, *32*(12), 2256-2266.

Wheaton, K. J., Thompson, J. C., Syngeniotis, A., Abbott, D. F., & Puce, A. (2004). Viewing the motion of human body parts activates different regions of premotor, temporal, and parietal cortex. *Neuroimage*, *22*(1), 277-288.

Wilkowski, B. M., Meier, B. P., Robinson, M. D., Carter, M. S., & Feltman, R. (2009). "Hot-headed" is more than an expression: The embodied representation of anger in terms of heat. *Emotion*, *9*(4), 464.

Willems, R. M., & Casasanto, D. (2011). Flexibility in embodied language understanding. *Frontiers in Psychology*, *2*, 116.

Williams, Lawrence E. & John A. Bargh. 2008. Experiencing physical warmth promotes interpersonal warmth. Science 322(5901). 606–607.

Williams-Whitney, D., Mio, J., & Whitney, P. (1992). Metaphor production in creative writing. *Journal of Psycholinguistic Research*, *21*,497-509.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic bulletin & review*, *9*(4), 625-636.

Wilson, R. A., & Foglia, L. (2011). Embodied Cognition. *Stanford Encyclopedia of Philosophy*.

Yu, N. (1995). Metaphorical expressions of anger and happiness in English and Chinese. *Metaphor and symbol*, *10*(2), 59-92.

Yu, N. (1998). *The contemporary theory of metaphor: A perspective from Chinese* (Vol. 1). John Benjamins Publishing.

Appendix A

Tables and Figures

TABLE I

SUMMARY OF PARTICIPANT DEMOGRAPHIC CHARACTERISTICS

Gender (%)		
	Female	65.45%
	Male	34.55%
Age		
	Mean	18.78
	SD	1.41
Bilingual/Multilingual? (%)		
	"No"	21.82%
	"A little"	7.27%
	"Somewhat"	14.55%
	"Yes"	56.36%
Vocabulary Score		
No Stimulation	Mean	9.09
	SD	2.07
Active Stimulation	Mean	9.26
	SD	2.23

TABLE II

SENTENCE STIMULI

Category	Subcategory	Action Word	Sentence	Familiarity Rating (1-7)
Literal	Nonmotor	N/A	The agency halted the funding	N/A
			The army supported the plan	
			The church altered the rules	
			The company discharged the employee	
			The music stimulated the fancy	
			The taxes distressed the poor	
			The aroma excited the senses	
			The court rejected the evidence	
			The leadership supported the scheme	
			The opposition ended the support	
			The rent distressed the tenants	
			The report distorted the facts	
	Motor	Bent	The worker bent the pipe	
		Pulled	The guard pulled the lever	
		Pushed	The secretary pushed the button	
		Squeezed	The baker squeezed the tube	
		Tickled	The nurse tickled the baby	
		Tossed	The referee tossed the coin	
		Cut	The kid cut the paper	
		Grasped	The daughter grasped the flowers	
		Pinched	The doctor pinched the skin	
		Shook	The man shook the drink	
		Stirred	The chemist stirred the mixture	
		Twisted	The electrician twisted the cable	
Metaphor	High Familiarity	Tickled	The aroma tickled the senses	6.038
		Tossed	The court tossed the evidence	5.962
		Bent	The report bent the facts	5.926
		Pulled	The agency pulled the funding	5.63
		Pushed	The army pushed the plan	5.56
		Squeezed	The taxes squeezed the poor	4.926
	Low Familiarity	Tickled	The music tickled the fancy	3.821
		Tossed	The company tossed the employee	3.893
		Bent	The church bent the rules	4.393
		Pulled	The opposition pulled the support	4.036
		Pushed	The leadership pushed the scheme	4.214
		Squeezed	The rent squeezed the tenant	4.179

Category	Subcategory	Action Word	Sentence	Familiarity Rating (1-7)
Nonsense	Nonmotor	N/A	The worker browsed the ball	
			The driver read the rope	
			The officer learned the lid	
			The Method dreaded the wall	
			The scheme proved the bolt	
			The skill summarized the coin	
			The violence increased the potato	
			the cat altered the fairness	
			The collection upset the banana	
			The empathy approved the tortilla	
			The box exploited the train	
			The note changed the boulder	
	Motor	Punched	The student punched the need	
		Tickled	The tabloid tickled the prices	
		Grabbed	The hospital grabbed the dissent	
		Twisted	The recession twisted the couch	
		Gripped	The media gripped the laziness	
		Caught	The attendant caught the gain	
		Grasped	The belief grasped the bottle	
		Threw	The classroom threw the pots	
		Squeezed	The crime squeezed the adventure	
		Pushed	The smell pushed the building	
		Seized	The book seized the pencil	
		Tossed	The concept tossed the mosquito	

Figure I. Anticipated Results – Sensibility task judgment times as a function of stimulation condition and stimulus group. Compared to sham stimulation, response times under anodal tDCS stimulation are expected to be faster for motor literal and motor metaphor sentences, but not for nonmotor literal sentences or nonsense sentences.

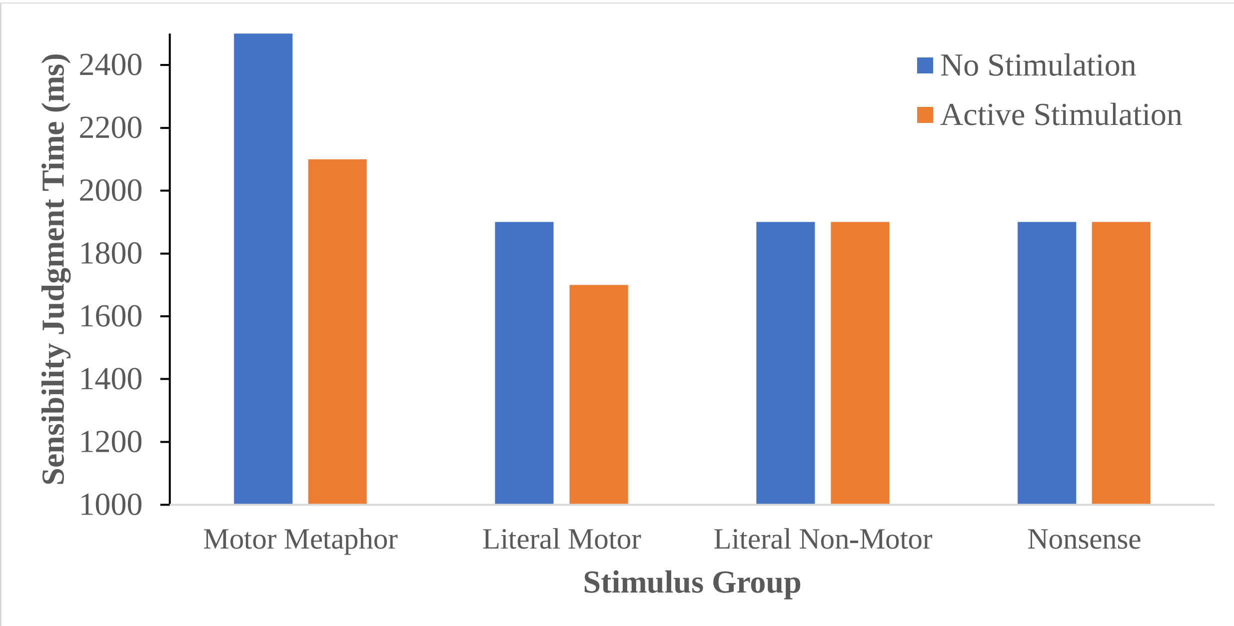


Figure II. Anticipated Results – Sensibility task judgment times as a function of stimulation condition and motor metaphor familiarity. The facilitatory effect of anodal tDCS stimulation is expected to increase as familiarity decreases. Hence, the difference between no stimulation and active stimulation is expected to be relatively small for highly familiar metaphors and relatively large for low-familiarity metaphors.

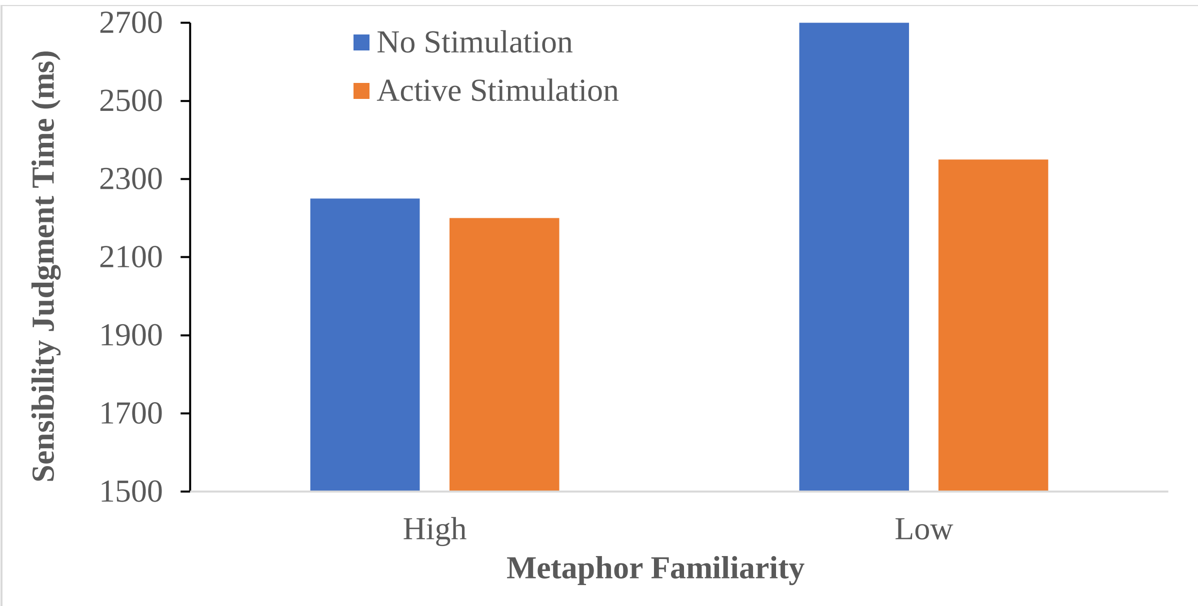


Figure III. Sensibility task judgment times (with standard errors) as a function of stimulation condition and stimulus group. Compared to no stimulation, response times under anodal tDCS stimulation were significantly faster for motor metaphor and motor literal sentences, but not for nonmotor literal sentences or nonsense sentences.

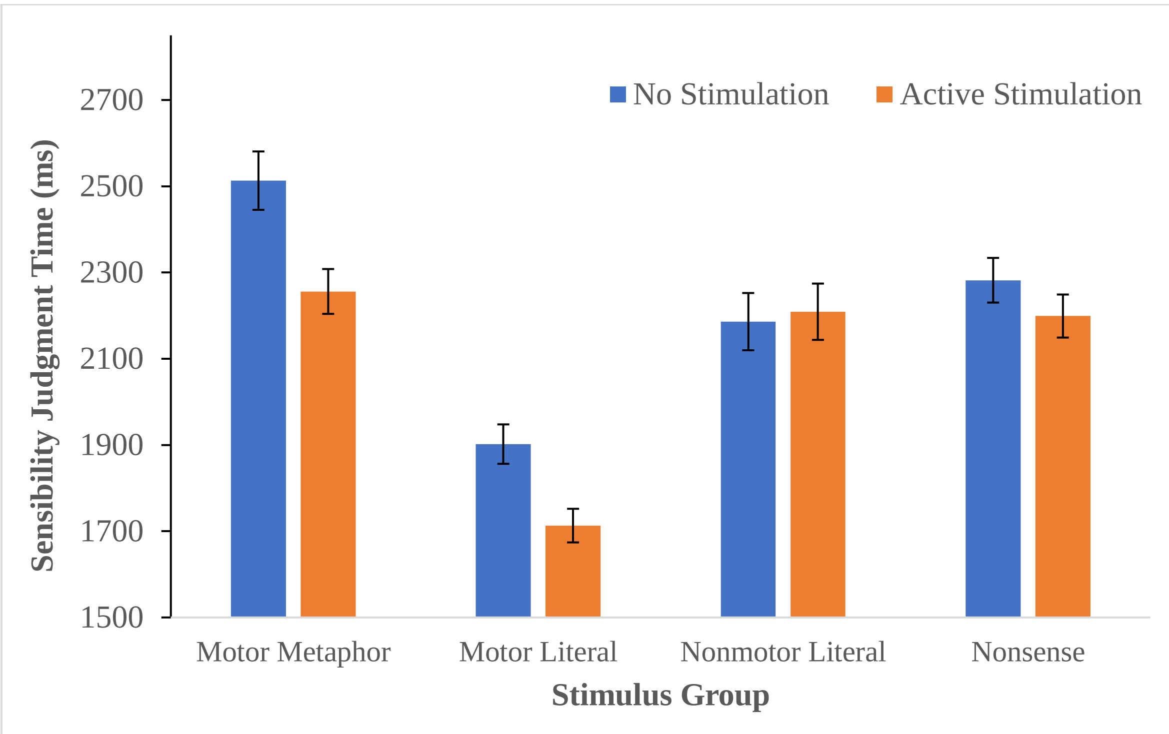
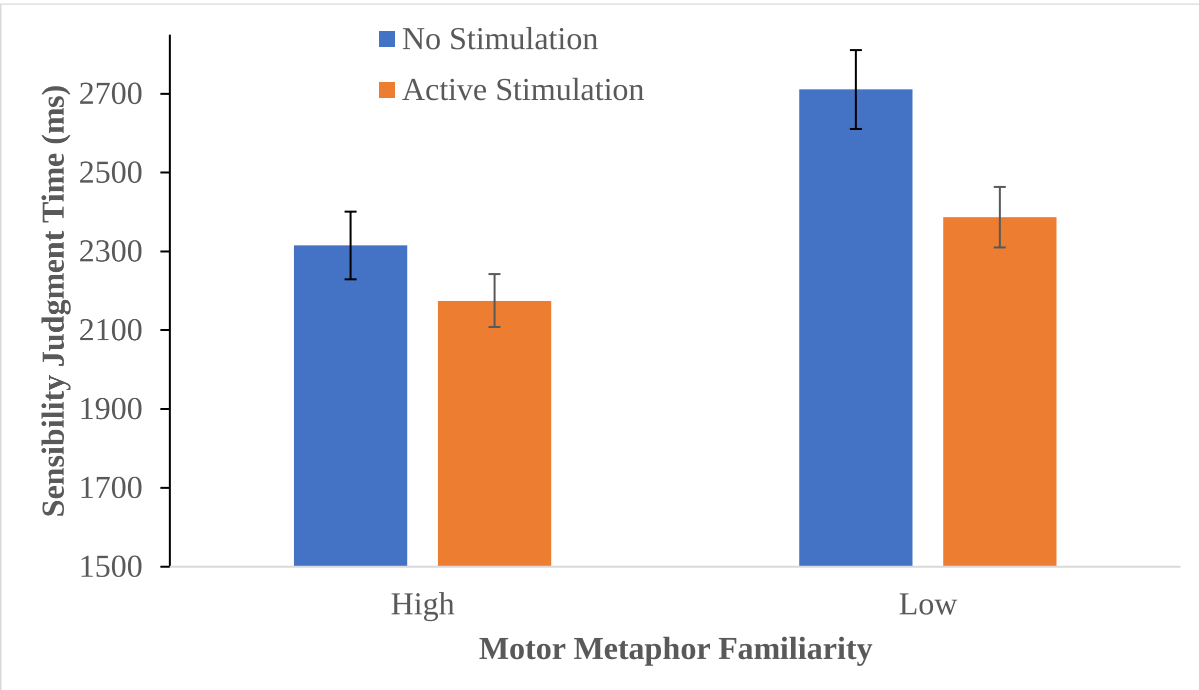


Figure IV. Sensibility task judgment times (with standard errors) as a function of stimulation condition and motor metaphor familiarity. Compared to no stimulation, response times under anodal tDCS stimulation were significantly faster for low-familiarity motor metaphors, but not for high-familiarity motor metaphors



Appendix B

UIC Vocabulary Quiz and Language History Questionnaire

Vocabulary Test (Version 6/09/2004) **Subject __________**

Directions: Choose the BEST definition for each word.

1. ASCEND
A. to go up or mount
B. consent
C. improve with time
D. to leave behind
E. to replace a leader

2. WARY
A. tired out
B. rude; uncouth
C. perturbed
D. brand-new
E. cautious; careful

3. INFINITESIMAL
A. very long
B. very slow
C. well defined
D. uncompromising
E. very small

4. INDIFFERENT
A. similar
B. unconcerned
C. diffident
D. solicitous
E. opposite

5. VERBOSE
A. slow
B. impressive
C. complicated
D. wordy
E. meaningless

6. OPAQUE
A. transparent
B. slippery
C. impenetrable by light
D. gem-like
E. financially well-off

7. SYNTHESIS
A. musical rendition of a written work
B. a theory of immoral behavior
C. the combination of parts to form a whole
D. watching or guarding
E. properties of artificial chemicals

8. SPONTANEITY
A. unwanted laughter
B. uncontrollable danger
C. unplanned action
D. unneeded socialism
E. stand-up attitude

9. VALIDATE
A. to prove
B. to get paid back
C. to expire
D. to run away
E. to complete successfully

10. MEAGER
A. not full, inadequate
B. to beg
C. without self-respect
D. in good shape, healthy
E. wise, full of advice

11. ECLECTIC
A. providential
B. of religious origins
C. purified
D. out of fashion
E. from various sources

12. IMPLAUSIBLE
A. could happen at any moment
B. not believable
C. unyielding
D. considered tactless
E. to serve or worship

13. INCONTROVERTIBLE
A. useless
B. prone to trouble making
C. indisputable
D. successful
E. unprotected

14. DISPERSE
A. to seize one's assets
B. to live in exile
C. to break up and scatter
D. to weaken connections
E. to make vacant

15. AUTONOMOUS
A. unknown identity
B. having many names
C. uncontrollable
D. independent existence
E. self-confidence

Language History Questionnaire

Subject # ________ (Version 12-12-2001)

Sex _________ Age _________ What country were you born in? ________________________

Years living in U.S. _________ Years in U.S. Schools _________

(1) What is the FIRST language you spoke? If your parents spoke two languages to you, list BOTH languages.

(2) List from MOST fluent to LEAST fluent all of the languages that you know (write on the back of this page if you need more space). Note that the language you learned first is not necessarily the language you now know best. Specify the age at which you began to learn the language (if it is your native language you should specify age as "birth") and where you learned it (e.g., school, home, church).

	Language	Age learned	Location learned
Most fluent	____________________	__________	__________________________
	____________________	__________	__________________________
	____________________	__________	__________________________
Least fluent	____________________	__________	__________________________

(3) Answer the following questions. Complete only those questions that apply to you.
At what age did you begin speaking **English**? __________
At what age did you begin reading **English**? __________
At what age did you begin speaking your most fluent language **OTHER THAN** English? __________
At what age did you begin reading your most fluent language **OTHER THAN** English? __________

(4) Complete the following ratings. If you think you are more proficient in either English or your OTHER language, your ratings should reflect this difference. Answer only those questions that apply to you.

	NOT fluent									VERY fluent
For ENGLISH:										
How fluent are you in speaking?	1	2	3	4	5	6	7	8	9	10
How fluent are you in understanding?	1	2	3	4	5	6	7	8	9	10
How fluent are you in reading?	1	2	3	4	5	6	7	8	9	10
For your most fluent language OTHER THAN English:										
How fluent are you in speaking?	1	2	3	4	5	6	7	8	9	10
How fluent are you in understanding?	1	2	3	4	5	6	7	8	9	10
How fluent are you in reading?	1	2	3	4	5	6	7	8	9	10

Appendix C

TDCS Screening Questionnaire and Comfort Rating Form

tDCS Screening Questionnaire

It is important that you answer all of the following questions truthfully. If any of the questions/terms on this form are unclear, or if you are unsure how to answer them, please do not hesitate to ask the researcher of the study.

	Yes	**No**
Have you ever had a seizure?		
Have you ever had a head injury resulting in a loss of consciousness that has required further investigation (including neurosurgery)?		
Do you suffer from migraines?		
Do you currently have a medical diagnosis of a neurological condition?		
Do you have any metal in your head (outside of the mouth) such as shrapnel or surgical clips?		
Do you have any implanted devices (e.g. cardiac pacemaker, brain stimulator)?		
Do you have a skin condition on your scalp that may have resulted in cuts or abrasions? (e.g. psoriasis)		
Do you have a head wound that has not completely healed?		
Have you ever had an adverse reaction to tDCS, or any other brain stimulation technique (e.g. TMS, tRNS)?		

ID#____________________ Date____________

tDCS Comfort Rating

Which number best describes how comfortable you are with 1 being very comfortable and 10 being extremely uncomfortable? (Circle participant's response)

1 2 3 4 5 6 7 8 9 10

Time Point____ Time____________

Which number best describes how comfortable you are with 1 being very comfortable and 10 being extremely uncomfortable? (Circle participant's response)

1 2 3 4 5 6 7 8 9 10

Time Point____ Time____________

Which number best describes how comfortable you are with 1 being very comfortable and 10 being extremely uncomfortable? (Circle participant's response)

1 2 3 4 5 6 7 8 9 10

Time Point____ Time____________

Which number best describes how comfortable you are with 1 being very comfortable and 10 being extremely uncomfortable? (Circle participant's response)

1 2 3 4 5 6 7 8 9 10

Time Point____ Time____________

Appendix D

Edinburgh Handedness Questionnaire

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, *put ++*. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
i. Which foot do you prefer to kick with?		
ii. Which eye do you use when using only one?		

Approval Notice
Initial Review – Expedited Review

November 6, 2019

Felix Pambuccian
Psychology
Phone: (651) 494-7939

RE: **Protocol # 2019-1116**
"Neuromodulation and Figurative Language"

Dear Dr. Pambuccian:

Members of Institutional Review Board (IRB) #3 reviewed and approved your research protocol under expedited review procedures [45 CFR 46.110(b)(1) and 21 CFR 56.110(b)(1)] on November 5, 2019. You may now begin your research.

Please note the following information about your approved research protocol:

Protocol Approval Date:	November 5, 2019 - November 4, 2020
Approved Subject Enrollment #:	1000
Performance Sites:	UIC

Research Protocol:

a) Neuromodulation and Figurative Language, Version 2.1, 11-05-2019

Investigational Device Manual:

a) The Brain Stimulator Instruction Manual, Version 3.0

Investigational Device: Brain Stimulator: The IRB determined that the device, tDCS machine, meets the requirements for non-significant risk as outlined in 21 CFR 812.2.

Documents that require an approval stamp or separate signature can be accessed via OPRS Live. The documents will be located in the specific protocol workspace. You must access and use only the approved documents to recruit and enroll subjects into this research project.

UNIVERSITY OF ILLINOIS AT CHICAGO
Office for the Protection of Research Subjects
201 AOB (MC 672)
1737 West Polk Street
Chicago, Illinois 60612
Phone (312) 996-1711

Recruitment Materials:

a) Neuromodulation and Figurative Language: Sona Script, Version 1, 10/02/2019
b) Neuromodulation and Figurative Language: tDCS Screening, Version 2, 10/28/2019

Informed Consent:

a) Neuromodulation and Figurative Language, Version 2, 10/28/2019

Please remember to:

→ **Use only the IRB-approved and stamped consent document(s) when enrolling new subjects.**

→ Use your **research protocol number** (2019-1116) on any documents or correspondence with the IRB concerning your research protocol.

→ Review and comply with the policies of the UIC Human Subjects Protection Program (HSPP) and the guidance ***Investigator Responsibilities***.

Please note that the UIC IRB has the right to ask further questions, seek additional information, or monitor the conduct of your research and the consent process.

Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact the OPRS office at (312) 996-1711 or me at (312) 355-4734. Please send any correspondence about this protocol to OPRS via OPRS Live.

Sincerely,

Carlisa P. Dixon, MHA
IRB Coordinator, IRB # 3
Office for the Protection of Research Subjects

cc: Gary Raney, Faculty Sponsor, Psychology, M/C 285
Michael E. Ragozzino, Psychology, M/C 285

Felix S. Pambuccian

Phone: (651) 494-7939
fpambu2@uic.edu

University of Illinois at Chicago (M/C 285)
1007 W Harrison St., Chicago, IL

EDUCATION

Ph.D. University of Illinois at Chicago **Anticipated August 2021**
Psychology (Cognitive)
Minor: Statistics, Methods, & Measurement
Dissertation:
Grasping the Idea – With Your Hands? A tDCS Investigation of Embodied Cognition in Motor Metaphor Processing

M.A. University of Illinois at Chicago, Psych **August 2017**
Psychology (Cognitive)

B.S. University of Minnesota **December 2013**
Psychology, *summa cum laude* with distinction
Minor: French

HONORS AND AWARDS

Harry S. Upshaw Award for Excellence in Teaching April 2021

PURR Mentor Award Fall 2019, Spring 2020, Fall 2020, Spring 2021

Awarded for undergraduate student mentorship through the Psychology Department Undergraduate Research Readiness (PURR) initiative, which matches graduate students with undergraduates from underrepresented backgrounds with the goal preparing students for future research careers

Psychology Department Travel Award 2016, 2017, 2018, 2019

UIC University Fellowship 2014-2019

TEACHING CERTIFICATION

Certificate in the Foundations of College Instruction August 2019
Graduate College, University of Illinois at Chicago
Coursework:

Seminar in College Teaching Fall 2018

Foundations of College Teaching Spring 2019

The Science of Teaching Psychology Fall 2018

Practicum in Teaching Psychology Spring 2019

Coursework Specific to Online Instruction
Overview of Online Instruction, University of Illinois Springfield Summer 2020

TEACHING EXPERIENCE

<u>Instructor of Record</u>

University of Illinois at Chicago, Chicago, IL

Statistical Methods in Behavioral Sciences — Spring 2019
Designed and taught course (in-person)

Research Methods in Psychology — Fall 2020, Spring 2021
Designed and taught course (online asynchronous)

Lake Forest College, Lake Forest, IL

Introduction to Psychological Science Lab — Fall 2019, Spring 2020

<u>Teaching Assistant</u>

Advanced Undergraduate Statistics — Spring 2020

Statistical Methods in Behavioral Sciences — Fall 2018, 2019

Theories of Personality — Summer 2018

Cognition and Memory — Summer 2016, 2017

Research Methods in Psychology — Spring 2015 – 2018

<u>Guest Lectures</u>

Statistical Methods in Behavioral Science — November 2018

Topic: Factorial ANOVA

Cognition and Memory — May 2017

Topic: Language Processing

PUBLICATIONS (ACCEPTED AND SUBMITTED)

Pambuccian, F. S., & Raney, G. E. (2021). A Simile is (like) a Metaphor: Comparing Metaphor and Simile Processing Across the Familiarity Spectrum. *Canadian Journal of Experimental Psychology*. doi: 10.1037/cep0000242

Ebiringah, O., Cervone, D., & **Pambuccian, F.S.** (2020). *Assessing the Psychological Salience of Social Identities: Interpretations of Ambiguous Situations as an Implicit Measurement Tool.* Manuscript submitted for publication.

MANUSCRIPTS IN PREPARATION

Pambuccian, F. S., & Raney, G. E. *Grasping the Idea – With Your Hands? A tDCS Investigation of Embodied Motor Simulation in Literal and Figurative Language Processing.* Manuscript in preparation.

Christofalos, A.L., & **Pambuccian, F.S.** *Resource Depletion Impairs Situation Model Comprehension*. Manuscript in preparation.

Miller, K. A., Christofalos, A. L., **Pambuccian, F. S.**, & Raney, G. E. *The effect of word frequency during idiom comprehension changes as a function of idiom familiarity*. Manuscript in preparation.

CONFERENCE PRESENTATIONS

Spoken Presentations

Pambuccian, F. S., & Raney, G. E. (2021, April). *A tDCS Investigation of the Role of Embodied Cognition in Metaphor Processing*. To be presented at the 93nd annual meeting of the Midwestern Psychological Association, Chicago, IL.

Pambuccian, F. S., & Raney, G. E. (2020, July). *Grasping the Idea – With Your Hands? A tDCS Investigation of Embodied Simulation in Literal and Figurative Action Word Usage*. Presented remotely at the 7th annual UK Cognitive Linguistics Association Conference, Birmingham, United Kingdom.

Pambuccian, F. S., & Raney, G. E. (2019, August). *How Metaphor and Simile Comprehension Change Across the Familiarity Spectrum*. Presented at the 4th annual Metaphor Festival Conference, Amsterdam, Netherlands.

Pambuccian, F. S., & Raney, G. E. (2019, August). *Hold onto the Idea or Kick the Habit? The Role of Embodied Cognition in Metaphor Processing.* Presented at the 4th annual Metaphor Festival Conference, Amsterdam, Netherlands.

Raney, G. E., Christofalos, A. L., **Pambuccian, F. S.**, & Bovee, J. C. (June, 2016). *Using Letter Detection to Explore High-Level Text Processing*. In Roy-Charland, Annie (Chair). The Missing Letter Effect: History, Models and Current Avenues. Presented at the meeting of the Canadian Society for Brain, Behavioral, and Cognitive Sciences, Ottawa, CA.

Poster Presentations

Pambuccian, F. S., & Raney, G. E. (2020, November). *Stimulating the Mind Helps Readers Grasp the Idea: tDCS Evidence for Embodied Simulation in Motor Metaphor Comprehension*. Presented at the 61st annual meeting of the Psychonomic Society.

Pambuccian, F. S., & Raney, G. E. (2020, April). *A tDCS Investigation of the Role of Embodied Cognition in Metaphor Processing*. Presented at the 92nd annual meeting of the Midwestern Psychological Association, Chicago, IL. (Conference canceled)

Pambuccian, F. S., Raney, G. E., & Carsel, T.S. (2019, October). *Research or Me-search: Do Students Learn Statistical Concepts Better Using Class-Generated Data?* Presented at the 18th annual meeting of the Society for the Teaching of Psychology's Conference on Teaching, Denver, CO.

Pambuccian, F. S., & Raney, G.E. (2018, November). *Metaphor and Simile Processing Across the Familiarity Spectrum*. Presented at the 59th annual meeting of the Psychonomic Society, New Orleans, LA.

Pambuccian, F. S., & Raney, G.E. (2017, November). *Using Resource Depletion to Examine Processing of Familiar and Unfamiliar Metaphors*. Presented at the 58th annual meeting of the Psychonomic Society, Vancouver, Canada.

Pambuccian, F. S., & Raney, G.E. (2016, November). *Beyond the word level: Using letter detection to investigate reading of metaphor phrases*. Presented at the 57th annual meeting of the Psychonomic Society, Boston, MA.

Pambuccian, F. S., & Raney, G.E. (2016, May). *Using letter detection to investigate reading of metaphor phrases*. Presented at the 88th annual meeting of the Midwestern Psychological Association, Chicago, IL.

DEPARTMENTAL AND COLLOQUIUM PRESENTATIONS

Pambuccian, F. S. (2020, September). *Do We Use Our Hands to Grasp the Idea? A tDCS Investigation of Sensorimotor Simulation in Metaphor Processing*. Spoken presentation at the University of Illinois at Chicago Cognitive Psychology Current Research Topics Brown Bag.

Pambuccian, F. S. (2019, February). *The Role of Embodied Cognition in Metaphor Processing*. Spoken presentation at the University of Illinois at Chicago Cognitive Psychology Current Research Topics Brown Bag.

Raney, G. E., Christofalos, A, L., Miller, K. A., **Pambuccian, F. S**., & Riaño, C. E. *Figurative Language Research at UIC*. (October, 2017). Spoken presentation at the DePaul University Psychology Department Brain and Language Lab.

Pambuccian, F. S. (2016, October). *Comparing processing of familiar and unfamiliar metaphors using a resource depletion manipulation*. Spoken presentation at the University of Illinois at Chicago Cognitive Psychology Current Research Topics Brown Bag.

Pambuccian, F. S. (2015, May). *Beyond the word level: Using the letter detection task to investigate metaphor processing*. Spoken presentation at the University of Illinois at Chicago Cognitive Psychology Current Research Topics Brown Bag.

MENTORED UNDERGRADUATE RESEARCH ASSISTANT PRESENTATIONS

Abuzir, L. K., & **Pambuccian, F. S.** *The Foreign-Language Effect on Empathy in English-Spanish Bilinguals.* (May, 2021). Spoken presentation to be presented at the 93rd annual meeting of the Midwestern Psychological Association, Chicago, IL.

Przybycin, A. P., & **Pambuccian, F. S.** *A Bilingual Advantage in Artificial Language Learning*. (May, 2020). Poster presentation at the 32nd annual Association for Psychological Science Convention, Chicago, IL. (Conference canceled)

Kosacz, D. J., & **Pambuccian, F. S.** *Does Disgust Impact the Severity of Moral Judgments? The Influence of Metaphoric Transfer*. (April, 2019). Poster presented at the UIC Research Forum.

Kosacz, D. J., & **Pambuccian, F. S.** *Metaphoric Transfer of Disgust in Morality Judgments*. (March, 2019). Poster presented at 5th annual University of Illinois at Chicago Psychology Cross-Program Conference.

PROFESSIONAL MEMBERSHIPS

American Psychological Association

Society for the Teaching of Psychology

Psychonomic Society