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ASSESSING THE ROLE OF BIOLOGY UNDERGRADUATES' METACOGNITIVE CALIBRATION AND NEURAL ACTIVITY DURING MODEL-BASED REASONING

by

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ASSESSING THE ROLE OF BIOLOGY UNDERGRADUATES' METACOGNITIVE CALIBRATION AND NEURAL ACTIVITY DURING MODEL-BASED REASONING

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University of Nebraska, 2022

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Metacognition refers to the critical awareness of or ability to monitor, regulate, control, and sequence of one's thoughts and performance. There is limited research that examines the relationship between metacognition and (a) academic performance and (b) general cognition among undergraduates. Moreover, there is an even greater paucity of literature that focuses more specifically on undergraduate biology students' neural activity in relation to their metacognition.

This study aimed to examine the relationship between undergraduate life sciences students' metacognitive calibration, i.e., their capacity to self-evaluate their own performance, and their behavioral performance and brain activity during a biological error reasoning task. Thirty-four undergraduate students (M_{age}= 19.47, 85% female) from a Midwestern university completed a model reasoning task during functional magnetic resonance imaging (fMRI). Two distinct groups of students with individual differences—Calibrated and Non-Calibrated—emerged based on the match of their task accuracy to their self-reported confidence in their accuracy.

General patterns indicated that participants tended to overestimate their performance. Findings indicated that task accuracy was associated with stronger activation in the left middle frontal gyrus when evaluating correct models. Additionally, students in the Calibrated group showed higher levels of activity in the anterior cingulate gyrus on trials they were confident on in the model evaluation task than students in the Non-Calibrated group. These results suggest that students in the Calibrated group are better at recognizing the need for effortful and strategic reasoning during trials that demand error detection and that they, therefore, deploy PFC during these trials. These findings also highlight metacognition, and specifically students' self-monitoring, as a core target for STEM educators to promote effective reasoning, as well as a need to nurture and foster metacognition and self-awareness in the classroom.

Keywords: metacognition, calibration, self-awareness, brain, biology, error detection

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CHAPTER I

INTRODUCTION

Self-regulation, the amount of control students have over their own cognition, motivation, behavior, and emotions, lies at the heart of learning. Self-regulation involves the extent to which students are functionally engaged in their learning acquisition while also being self-motivated and behaviorally active (Zimmerman & Martinez-Pons, 1988). Successful and efficient learners demonstrate high levels of self-regulation in order to accomplish a task or a goal by correcting and monitoring the effectiveness of strategies, as well as by evaluating and self-reflecting on past behaviors to gain more control over future events (Roebers, 2017). Additionally, self-regulation includes multiple metacognitive skills. Metacognition refers to one's knowledge of cognition (declarative) and self-awareness of the need to understand and control one's learning and thinking processes. When learners develop high self-regulation and metacognitive skills, they can consciously revise and reconstruct concepts to advance their knowledge (e.g., conceptual change), which is key to learning.

Defining Metacognition

In cognitive research, the discovery and study of metacognition has been widely recognized. The initial, yet provisional, definition of metacognition is "thinking about thinking" (Flavell, 1979). However, a more precise definition seeks to understand metacognition as the critical awareness of or ability to monitor, regulate, control, and sequence one's thoughts and performance (Cross & Paris, 1988). Contemporary conceptualizations generally divide metacognition into two distinct classifications: knowledge about cognition (including self-monitoring) and self-regulatory mechanisms

(Cross & Paris, 1988; Flavell, 1979; (Kruger & Dunning, 1999). Self-monitoring is concerned with knowing how well one is performing and with recognizing whether one is likely to be accurate or erroneous in judgment or behavior. On the other hand, metacognitive regulation is the process of organizing one's cognition, including planning, being aware of one's comprehension, task performance, and evaluating the efficacy of strategies. Self-monitoring and metacognitive regulation are both important for this study because they are skills that help students learn how to self-assess their behavior and to evaluate the effectiveness of their learning strategies.

In the wake of Cross and Paris (1988), Schunk and Zimmerman (1994) were the first researchers to integrate self-regulation and metacognition into academic settings. In his self-regulated learning model, Zimmerman (2013) focused on the learner's beliefs about their ability to engage in actions, thoughts, emotions, and behaviors in order to achieve a goal, as well as on how they self-monitor and self-reflect on their progress. Research indicates that both self-regulation and metacognition are essential to learning because students who self-regulate tend to have both high self-efficacy in performing a specific task and high levels of self-discipline (Bandura, 2001). These qualities mean that self-regulated learners are also more likely to persist in the face of difficult learning tasks (Paris & Newman, 1990; Winne, 2010). Self-regulation is a technique that allows students to view learning within a proactive, constructivist approach, rather than considering the learning process as a passive act where learning occurs as the result of instruction imposed from the outside (Zimmerman, 2002).

As Zimmerman (2002) noted, several executive control functions are necessary for students to complete complex academic tasks. First, learners need to be able to understand their general level of knowledge, as well as their thought processes (metacognitive knowledge) and to regulate their knowledge. For example, students with effective metacognitive knowledge skills can distinguish concepts they have already mastered from those they need to continue to study. Second is monitoring, which includes assessing comprehension while progressing through a task, as well as evaluating and revising the effectiveness of current strategies. The third and last executive functions are failure detection and failure correction. While failure detection refers to correctly identifying and detecting errors, failure correction indicates going back and fixing any known errors. In general, if learners lack the skills to produce correct answers, they cannot determine whether their answers are right or wrong, which exposes undeveloped skills in the areas of metacognitive judgment, self-awareness, and self-calibration.

In educational psychology, calibration is defined by how accurately individuals assess their confidence in their own knowledge (Stone, 2000). Effective self-monitoring relies on accurate or well-calibrated performance assessments (Pieschl, 2009). Research studies that examine calibration often ask participants to predict the correctness of their responses to test items (Wollenschläger et al, 2016). Calibration accuracy typically is defined as the degree of comparison between learners' true and the learners' self-predicted task performance (Andrade, 2019), where learners' levels of confidence should correlate positively with their performance.

Students who lack regulatory skills tend to make inaccurate judgments of their own performance. In the absence of accurate external or self-delivered feedback, learners are unlikely to recognize the need to implement effortful strategies that improve performance (Zimmerman, 2013). Conversely, calibrated performance judgments are likely to support both reflection and recognition of the need to deploy cognitive resources. In addition to self-calibration and self-awareness, reported self-confidence in one's performance is an important concept in understanding metacognition. Measures of confidence allow researchers to compare the level of students' confidence to their accuracy in performances. Confidence estimates tend to be higher when correct and lower when incorrect (Fleming et al., 2010). However, more specifically, lower-performing students tend to be more overconfident in their performance predictions, and higher-performing learners tend to be more accurate or underconfident (Dunning et al., 2003; Kruger & Dunning, 1999; Hacker, 2000). Assessments of students' confidence in their performance offer one means of assessing their self-awareness and calibration of their own performance. Research aims to reveal how self-regulation and calibration can, ultimately, help students become more accurate in and self-aware of their self-monitoring skills and regulating their knowledge acquisition.

Limited research exists on the neural correlates of self-regulation and metacognition. Zimmerman's Self-Regulated Learning theory infers that students with efficient task strategies possess higher levels of self-monitoring skills. That is, students with high metacognitive calibration will also have high self-regulation and self-awareness skills, suggesting that they might be inclined to engage in error checking and in error detection. Additionally, these students might also have higher activation in the prefrontal cortex (PFC), given the important role this brain region plays in self-awareness and executive function (Friedman & Robbins, 2022).

Purpose of the Present Study

The purpose of this study is to investigate the relationship between undergraduate life sciences students’ metacognitive calibration and their behavioral performance and brain activity when engaged in reasoning about the accuracy of biological models. Model-based reasoning is a core area of STEM education and offers a relevant context for understanding how metacognitive calibration contributes to STEM learning. There is currently only limited research that examines the relationship between metacognition and academic performance among undergraduates as a whole. Although common themes frequently appear in the self-regulation and metacognitive literature, there is an even greater paucity of literature that focuses more specifically on undergraduate biology students' neural activity regarding metacognition. Given the opportunity to conduct such research, several intriguing questions arise. The main research questions guiding this thesis are as follows:

1. *Because recent research has indicated that students tend to overestimate their metacognitive and self-regulatory skills, can we identify whether life sciences undergraduate students attending a Midwestern university can be classified as Calibrated or Non-Calibrated based on performance assessments?*
2. *In light of question one above, if students can be grouped based on calibration, do the members of the two groups differ in neural activity?*
3. *How does students’ calibration relate to academic achievements, such as Grade Point Average (GPA) and to their general cognitive performance?*

Our laboratory study hypothesized that undergraduates can be categorized as either Calibrated or Non-Calibrated based on their confidence and task performance.

Furthermore, we predicted that Calibrated students would exhibit higher activity in anterior brain regions, including the lateral prefrontal cortex (PFC) and anterior cingulate cortex (ACC), especially when evaluating models that contained misconceptions or errors. The rationale for these hypotheses is based on the literature reviewed in the next chapter.

CHAPTER II

LITERATURE REVIEW

Metacognition and its Relation to Self-Regulation

Over the past several decades, the topic of metacognition has gained attention within the field of educational psychology. In the late 1970s, Flavell broadly coined and defined the term metacognition as "thinking about thinking." Flavell (1979) focused on the interaction among metacognitive knowledge, experiences, goals, and strategies. He suggested that the developmental process of metacognitive skills is contingent on how learners create, evaluate, and revise tasks, goals, and strategies. Zimmerman (1986) further defined metacognition as the ability to adjust behavioral, environmental functioning in response to changing academic demands. In addition, Pintrich (1994) defined academic metacognition as a construct comprised of three major elements. The first is active control over learning-related behaviors. The second involves how students learn to control their emotions (e.g., self-regulation of motivation and affect). The third is the amount of control the individual has over various cognitive strategies for learning (e.g., rehearsal and memory strategies).

Over time, educational psychologists have further developed the definition of metacognition to incorporate the cognitive awareness, management, and control of one's thoughts (Cross & Paris, 1998; Kuhn & Dean, 2004). Schraw and colleagues (2006) also suggested that metacognition should be classified under self-regulated learning because self-regulated learning involves concepts of self-awareness, motivation, and higher cognitive processes. While the definition continues to be updated, researchers tend to agree that metacognition consists of the following two components (Cross & Paris, 1988;

Flavell, 1979): knowledge about cognition (metacognitive knowledge) and regulation of cognition (metacognitive regulation). Metacognitive knowledge is the knowledge, awareness, and deeper understanding of one's cognitive processes, which is expanded through self-evaluation.

One main component of metacognition regulation is the individual's monitoring of cognition through planning, regulating, and evaluating (Cross & Paris, 1988). Metacognitive research primarily focuses on individuals' subjective, introspective responses following their performances. Metacognitive monitoring and judgments are typically studied by comparing the accuracy of individuals' responses on tasks to their level of confidence about their performances. For example, Stanton et al. (2015) explored biology undergraduates' metacognitive monitoring and judgments by examining both their exam performances and their study habits. While most students were willing to reflect on and adjust their study plans, researchers found that many actually do not identify appropriate learning strategies or carry out their new plans. In other words, students may need additional help to improve their metacognitive knowledge, which can, in turn, enhance their study habits and strategies.

Following, Mathabathe (2019) explored students' reasonings and justifications for their perceived academic performances on pre-and post-test chemistry tests to understand the relationship between confidence levels and academic performance. The research found that the learning experience in chemistry was most productive for students who both acknowledged and articulated that they did not know what they did not know and whose reported confidence matched their lack of knowledge. Additionally, students who were more realistic (calibrated) in their performance evaluation tended to be more certain in their confidence judgment ratings in the posttest (e.g., “don’t feel confident,” “it’s right”) than students who were overconfident in their judgments of performance. Effective calibration is critical to overall learning, as students who are more aware of their performance can use self-regulatory skills to create, monitor, and revise strategies for subsequent performances (Magno, 2010; Siegesmund, 2017).

Researchers debate whether metacognitive judgments stem from mental activity, such as reflective evaluations of one’s knowledge, or whether metacognitive judgments relate to inferences based on heuristics or personal experiences (Lyon & Zelazo, 2011). In viewing metacognition from a developmental framework, research suggests that metacognitive judgments can be recognized and probed based on heuristic cues (Schwartz, 2002; Koriat & Ackerman, 2010), which also explains why metacognitive judgments can be described as “intuitive feelings” (Price & Norman, 2008) concerning performance. However, Dinsmore, Alexander, and Loughlin (2008) noted that metacognitive judgment also should emphasize both learner development and how the learner interacts with the environment to maximize and optimize the ability to learn. In general, metacognitive self-monitoring and judgments are based on a variety of internal and external cues (Ackerman & Thompson, 2017), including those that derive from the complexity of the task and from one’s experiences of attempting the task (e.g., reflective evaluations). While the basis for metacognitive judgment in intuition or self-reflection remains unclear, the literature is consistent in suggesting that calibration accuracy represents an important process supporting self-regulated learning.

Metacognition: Links to Academic Performance and Confidence

The accuracy of metacognitive judgments tends to increase throughout childhood and into young adulthood (Schneider & Lockl, 2008; Weil et al., 2013). Additionally, students' metacognitive skills progressively become more concordant with their actual performance with age (Schneider, 1998). This association is most likely attributable to students' increase in content knowledge and language skills over time, which can help explain why they develop an increasingly more accurate foundation for assessing the quality of their performance (Kruger & Dunning, 1999). Zelazo and Cunningham (2007) also noted that the accuracy of metacognitive judgments can improve with age because of students' increasing ability to "psychologically distance themselves from their ongoing mental activity" which helps them gain a "broader perspective of their cognitive activity and its likely outcomes." (Lyons & Zelazo, 2011, p. 379).

One method for studying metacognitive judgments or students' calibration is to measure and compare their confidence and their academic performance. Generally, higher-performing students demonstrate high accuracy when predicting their test performance scores; lower-performing students show strong overconfidence in their predictions (Hacker et al., 2000). While metacognitive judgments improve with age, the degree to which students can accurately self-assess and self-evaluate their performances involves their self-awareness of their knowledge deficits. More recently, Morphew (2021) examined the role of students' metacognitive monitoring in a physics course by comparing their predicted test performance and actual performance. The findings indicated that low-performing students were less accurate at predicting their exam performances and were less likely to improve their metacognitive calibration than were high-performing students, supporting the indicators described in previous literature. The roles of metacognitive monitoring and confidence in academic achievement can be viewed as a form of thought validation. Metacognitive confidence is a student's level of belief in his or her ability to achieve a standard of accuracy (Fleming & Lau, 2014). In general, positive beliefs and thoughts on exam performances increase confidence, while negative views reduce confidence and performance (Moreno, Briñol, & Petty, 2021).

While calibration feedback can help students improve their monitoring skills (Miller and Geraci, 2011), low-performing students who received feedback about the accuracy of their predictions, surprisingly, seemed to respond by becoming increasingly overconfident in their work, even though their test performance scores did not improve (Miller & Geraci, 2011; Callender et al., 2015; Morphew, 2021). Clayson (2005) noted that students' demonstrable level of competency could explain the discrepancy between confidence and actual performance. In other words, students who do not know what they do not know (lack of metacognitive knowledge) lack the cognitive ability to recognize or be aware of the changes necessary in order to develop more effective skills or strategies. Another hypothesis suggests that those students actually are aware of their knowledge deficits, but that they nevertheless choose to be consistently overconfident in their abilities, seemingly demonstrating resistance to recognizing that they have a knowledge acquisition problem. Collectively, the literature suggests a strong degree of overlap between students' levels of metacognitive calibration and their performance.

Metacognition and Intelligence

Another plausible mechanism by which metacognition might relate to achievement is via their mutual relation to students' intelligence. However, there is only limited research that investigates precisely how metacognition is linked to general intelligence. College students with learning disabilities exhibit significant difficulties in various academic domains, including reading, writing, math, and science, which increase their risk for dropping out of college as compared to students who do not have learning disabilities (Trainin & Swanson, 2005; Zeleke, 2004). However, with proper academic support and with training in skills for self-regulation, students with learning disabilities can achieve normative levels of success. For example, Trainin and Swanson (2005) found that GPA and academic achievement increased when metacognitive learning strategies and help-seeking activities were available for students with reading and learning disabilities. In other words, metacognitive strategies can help all college students, regardless of ability, to regulate and monitor their learning process by managing time, by understanding how to study efficiently, and by creating a healthy and nurturing learning environment (Pintrich, 1994). These findings suggest a limited overlap between metacognition and intelligence.

In addition, some studies suggest that it is students' beliefs about intelligence, as opposed to their measured performance on cognitive assessments, that are most closely linked to metacognition. Students who consistently, effectively, and accurately regulate and monitor their learning tend to be more successful learners because they are better at interpreting metacognitive cues (Miele & Molden, 2010; Finley, Tullis, & Benjamin, 2010). Learners who accurately report what they have learned are monitoring their learning and have better control over their metacognitive knowledge than those who inaccurately report what they have learned (Thiede, Anderson, & Therriault, 2003). Peng and Tullis (2019) studied both how beliefs about the nature of intelligence affect learners' metacognitive control and how those beliefs impact students' study choices. The researchers found that students' implicit assumptions of intelligence affect their level of engagement, which, in turn, affects their goals and metacognitive control. For example, learners who view intelligence as malleable and flexible showed greater mental engagement and stronger memory during cognitive tasks (Peng & Tullis, 2019). Overall, there is very limited literature examining the overlap between intelligence and metacognition but the small amount of research that does exist indicates that the overlap is minimal and that any intersections between metacognition and intelligence may be explained by student belief systems.

Metacognition and the Brain

Few studies address how metacognitive skills are reflected in specific brain activation. The prefrontal cortex (PFC) is important for metacognition (Shimamura & Squire, 1986) and self-awareness (Mansouri et al., 2017), and metacognitive judgments are linked to activation in the medial PFC (Fleming, 2021). Though neuroimaging literature, in general, has studied metacognition on arbitrary tasks or in terms of thinking about the self rather than studying metacognitive calibration in relation to authentic learning tasks. Fleming and colleagues (2010) MRI to examine individuals' introspective and metacognitive ability with respect to task performances. The researchers suggested that the anterior and dorsolateral PFC play a central role in metacognitive sensitivity, the ability to discriminate between correct and incorrect stimuli. Additionally, in a large-scale functional Magnetic Resonance Imaging (fMRI) study, Molenberghs and colleagues (2016) investigated individuals' differences in metacognitive ability and subjective feelings of confidence while performing high level social and cognitive tasks. Their study found that higher metacognitive accuracy was associated with decreased activation in the anterior medial PFC, which is linked to perception and autographical memory. Additionally, researchers found that an increase in reported confidence was linked to lower metacognitive accuracy on the social and cognitive tasks, indicating that individuals tend to overestimate their performance, which can undermine the accuracy of their metacognitive judgment. This limited literature on the neural mechanisms involved in metacognition, therefore, suggests that the dorsolateral and anterior medial PFC may be centrally involved in metacognitive calibration such that greater activity in these areas is associated with higher levels of self-awareness and metacognitive accuracy.

Conceptual Change in Science Learning and its Relation to Metacognitive Calibration

One mechanism via which metacognitive calibration may be linked to scientific learning is by affording greater potential for conceptual change. Students learning scientific concepts must be able to actively develop their learning process; they need to learn how to connect new concepts and relationships with prior knowledge, as well as how to integrate those new pieces of knowledge with existing knowledge (Dong et al., 2020). For conceptual change to occur, learners must first become dissatisfied with their existing conceptions and then find the new conception to be plausible (Posner et al., 1982). Conceptual change is important because learners must consciously revise and reconstruct concepts in order to advance their knowledge. However, concepts tend to be difficult to change or correct when learners hold misconceptions (Dole & Sinatra, 1998; Nadelson et al., 2018). In the “hard” sciences such as physics, misconceptions fall away quickly in the face of measurable, concrete facts, which resist being altered by subjective opinion.

As we move toward biology and away from the seemingly fixed nature of matter, we open the door to more fluid speculation and interpretation about why events happen in the biological world in the way that they do. Now, there is room for misconceptions to emerge in the way that students think about the biological world. Many of these misconceptions can emerge at an early age, can be based upon unscientific sources of knowledge, or be exacerbated by formal education and linger for months and years (Coley & Tanner, 2015). Unfortunately, ineffective pedagogical strategies experienced throughout one's early education can entrench misconceptions in the classroom setting. For example, young children often think that plants are not living things in the sense that they do not have complex ecological systems required for survival (Venville, 2004). Other common biology misconceptions among students include the notion that plants get their food from the soil or that genes and alleles are the same concept (Tekkayam, 2002). Lack of, or poor, metacognition can predict the extent to which learners ignore new information and can predict the degree to which they are unwilling to change their minds, even when they receive information that indicates they were wrong about their original belief (Fleming, 2021). Though, for learners who hold misconceptions, conceptual change is more likely to occur when a scientific viewpoint is offered which causes some cognitive conflict (e.g., error detection) (Broughton et al., 2010). Conceptual change occurs when students can allow inaccurate prior knowledge to be replaced by accurate or updated concepts.

The students' ability to embrace conceptual change is especially relevant for science learning. The relationship between metacognitive skills and conceptual change must exist because individuals routinely recognize existing conceptions, evaluate them, and decide whether to reconstruct their understanding of a concept or topic, a process that requires metacognitive ability (Gunstone & Mitchell, 2005). Students need to be able to recognize that they are making errors before they can revise their concepts. Metacognitive calibration may be the first critical step in the process of reconstruction. Students who are more metacognitively aware of misconceptions about a given topic are more likely to develop a deeper understanding of a concept or topic (e.g., having correct knowledge), decreasing the likelihood of developing misconceptions (Pieschl et al., 2021). On the other hand, students who are unaware of their misconceptions might be overconfident about or overly satisfied with their misconceptions (i.e., they do not know what they do not know) (Ehrliner et al., 2008; Pieschl et al., 2021). This idea suggests that metacognitive calibration can be a pivotal mechanism for enlightenment while correcting misconceptions.

Conceptual change, as it relates to science and learning science, requires students to have deep cognitive engagement in order to reach a point of dissatisfaction with prior conclusions which leads to the desire to accurately revise and reconstruct their knowledge (Nadelson et al., 2018). Student must be able to reach a stage of dissatisfaction which allows them to transition into learning new concepts in domains where they already possess functioning concepts (Smortchkova & Shea, 2020). However, there is little investigation into the role of metacognition in conceptual change, most likely because of the fundamental difficulties in designing an experimental route that would ensure scientifically sound results. We do know, however, that learners engage in self-reflective and self-evaluative thinking in order to match new pieces of information that examines, evaluates, and, ultimately, recognizes newer concepts which, then, replaces incomplete or inaccurate information within the students' body of understanding (Schunk & Ertmer, 2000; Posner et al., 1982).

Brain Activity During Error Detection

While there are no apparent studies that have examined neural activity in relation to science learning and metacognition simultaneously, limited literature on neural regions involved in science cognition highlights its dependence on prefrontal regions. Masson and colleagues (2014) used fMRI to compare novices and experts in science when asked to evaluate the accuracy of how simple electrical circuits work. The researchers found that error detection and conflict monitoring mechanisms play a role in observed differences in brain activity between novices and experts. This finding also indicated that experts, when evaluating scientific circuits, activated more brain regions, particularly those associated with inhibition (e.g., anterior cingulate cortex (ACC), ventrolateral PFC (VLPFC), and dorsolateral PFC (DLPFC) than novices, who tended to activate the DLPFC solely.

Similarly, Brault Foisy et al. (2015) found that the ACC and PFC play distinct roles in cognitive control during scientific reasoning. Individuals activate the ACC when they provide both correct and incorrect responses to scientific conceptions, whereas only the dorsolateral PFC is activated when individuals give correct answers. Potvin and colleagues (2020) recruited chemistry professors to test their cognitive knowledge by examining their inhibitory control response and common misconceptions using fMRI. The researchers found that both the left DLPFC and left VLPFC exhibited greater activation when participants were presented with scientific statements containing misconceptions, supporting previous research linking DLPFC to the resolution of misconceptions. In their review paper, Vaughn, Brown, and Johnson (2020) focused on the educational neuroscience framework of conceptual change by examining brain activation and cognitive processes linked to conceptual change in science-related tasks. When individuals view tasks that involve mental reconstruction of scientific models, researchers noted significant activation in the ACC, VLPFC, and DLPFC.

General Summary & Limitations of the Literature

Vast potential exists in educational neuroscience research to examine both the cognitive and affective changes in learners. In general, recent neuroimaging literature has determined, in fact, that a relatively small and well-defined area of the brain, which includes the ACC, DLPFC, and VLPFC, is consistently involved when processing scientific conceptions and misconceptions. However, more studies are needed to understand the relationship between learners' metacognition calibration and performance, as well as to understand how metacognition calibration and performance are reflected in the brain. More specifically, more research needs to examine the role of metacognitive calibration in conceptual change in science. While most science neuroimaging studies have been done with physics students, limited research on students in biology and life sciences exists, largely because of the difficulties in designing tasks that capture the complexity of biological systems and that still allow for scientific rigor. There are reasons to believe that resolving misconceptions in life sciences is as important as in physics, as recognizing these errors in biological thinking (e.g., erroneous ideas about the nature of evolution or about the links between DNA and protein formation) is central to deep conceptual understanding.

Research has revealed that lower-performing students tend to report being overconfident or overestimating their performances more than higher-performing students (Hacker et al., 2000; Miller & Geraci, 2011). However, the reason for this association remains unclear. One explanation is the “double curse,” in which low-performing students are both incapable of assessing their performance and unaware of their low metacognitive skills (Ehrlinger, Johnson, Banner, Dunning & Kruger, 2008). Another interpretation holds that low-performing students are aware of their performance level but nevertheless continue to overestimate their abilities. More recently, counter to the double curse, Miller and Geraci (2011) found that low-performing students are, in fact, somewhat aware of their low metacognitive judgment and calibration skills. Also, while there is a lack of studies investigating the direct relationship between metacognition and intelligence and those examining how metacognition can predict academic achievement. Again, further research is needed to address these questions.

While research reveals more about the relation of students’ calibration levels to academic performance, a surprisingly limited amount of research examines which areas of the brain are involved in metacognitive skills or how these regions are deployed during complex academic tasks. Indeed, most neuroimaging research on metacognition has not been conducted in the context of authentic learning tasks, despite the central relevance of metacognition to learning-related conceptual change. Likewise, only a limited body of research focuses on the neuroscientific framework of error detection which could link metacognition calibration skills to academic performance. There is a large and growing body of research on conceptual change and science learning within educational psychology; however, integration with neuroscientific research is far less common. This thesis will consider whether lateral PFC activity is related to higher levels of calibration in order to understand more about the ways in which metacognition facilitates science learning.

CHAPTER III

METHODS

Participants

Thirty-five undergraduate students participated in the study for monetary compensation. They were recruited through class announcements from an introductory life sciences course at a large Midwestern university. Students were screened to ensure that they did not have a learning disability, attention-deficit or hyperactivity disorder, experience of concussion, or other neurological diagnosis that might impact neural response patterns and that they had no contraindications to MRI. One student was excluded from analyses because they consistently gave the same response to every task trial. Of the final analytic sample (Valid N = 34, M_{age}= 19.47, SD_{age} = .45), 26 (76.47%) were first-year freshmen, six (17.65%) were sophomores, and two (5.88%) were juniors. Three (8.82%) were first-generation college students. Thirty (88.24%) were European American/White, one (2.94%) was Hispanic, two (5.88%) were Asian, and one (2.94%) identified as both European American/White and Hispanic. All but two students were native English speakers, and 29 (85%) were female, the remainder identifying as male. The average grade-point average (GPA), on a 4.0 scale and collected through a third party from the Registrar’s Office, was 3.61 (SD = .49).

Materials

All procedures were approved by the university’s Institutional Review Board, and participants provided written, informed consent to participation. Scans were also sent to a radiologist for review and students were informed of any incidental findings, with all of these being limited to sinus congestion. Students were compensated with $50 cash after attending a 2-hour appointment at the university's imaging center, where they completed an fMRI task.

Students underwent MRI in a 3 Tesla Siemens Skyra scanner using a 32-channel head coil. First, a T1-weighted MPRAGE was acquired (TR = 1, TE =2.95ms, voxel size = 1mm3, flip angle = 9, field of view = 270, 176 sagittal slices) for registration purposes. This scan was followed by T2*-weighted echoplanar images (TR = 1s, TE = 25ms, 3 mm voxels, flip angle =90, FOV = 224mm) collected during the model evaluation task.

Procedures

Model Evaluation Task

In the scanner, participants evaluated a series of models, formatted as flow charts, diagrams, or textbook-like images, that captured a breadth of content from the Introduction to Life Sciences course (e.g., human evolution, the central dogma, genetic mutation). Stimuli were designed to examine the participants' ability to detect errors and inhibit misconceptions (see Figure 1). To provide context for the model, students first saw a two-second prompt. They then viewed a model and prompt for ten seconds, after which they could take up to 30 seconds to indicate via a response pad whether the model was correct or incorrect. Lastly, participants were cued to indicate whether they were confident in their response (yes or no). Participants completed three separate, randomly-ordered runs (approximately five minutes each). Each run was composed of twelve randomly-ordered trials. Most models had two incorrect versions for every correct one, with 14 total correct trials and 22 error-containing trials. Trials were followed by a baseline rest period lasting two to ten seconds, during which students saw random images extracted from the model stimuli.

Following the above task that required the use of the MRI scanner, participants were then asked to circle on a printed sheet where they believed the error in the model was based on their responses in the scanner. They also provided a short rationale for the errors they indicated. Participants were not made aware whether their answers to the model evaluation task were correct or incorrect.

Cognitive Assessments and Surveys

Participants also completed the Kauffman Brief Intelligence Test-2 (KBIT-2) (Kaufman & Kaufman, 2004) to assess their verbal and non-verbal reasoning, which is an approximate measure of intelligence and general cognitive ability. After the cognitive assessment, participants completed a short Qualtrics survey to collect basic demographics. In that survey, participants completed Baldwin, Ebert-May, and Burns's (1999) College Biology Self-Efficacy assessment to determine their self-reported confidence in using biology in classrooms and daily lives, with 1 being "totally confident" and 5 being "not at all confident." Baldwin, Ebert-May, and Burns (1999) found three substantial factors that emerged from their factor analysis of the Biology Self Efficacy measure. Factor 1 represented students' reported confidence in writing and critiquing biological ideas through laboratory reports, as well as using analytical skills to conduct biological experiments (eight questions). Factor 2 focused on students' reported confidence in generalizing skills learned through current and future biology and science courses, as well as using scientific approaches to solve problems (nine questions). Last, Factor 3 related to students' reported confidence in applying biological concepts and skills to everyday events (six questions) (p. 402).

Last, participants filled out a modified version of the Positive and Negative Affect Scale questionnaire. This scale was comprised of 12 items, with eight items measuring positive affect and four items measuring negative affect (see Appendix A). Participants were asked to indicate, on a scale of one to five, their levels of each of the 12 emotions while completing the fMRI activities, with one indicating low levels of that emotion and five indicating high levels. From the survey, responses to the emotions interested, motivated, attentive, and determined were used to compute a new variable called Engagement.

Data Analysis

For each trial, we used SPSS (IBM Corp., Released 2020) to calculate whether students' confidence matched their accuracy. A response was designated 'over-confident' if students were confident but incorrect, 'under-confident' if they were not confident of an accurate response, or calibrated if accuracy and confidence corresponded. Participants were then classified as Calibrated (N = 19) if the absolute discrepancy between their total accuracy and total confidence was < 4; and Non-Calibrated (N = 15) if the discrepancy was > 4. (see Table 1 for Demographics of these two groups). Here, the cutoff was determined for these groups to be four because that was the absolute average discrepancy between total accuracy and confidence. We also examined the effects of over-estimating performance: students with > 8 'over-confident' responses were considered Overconfident (N = 19), as opposed to Calibrated/Underconfident (N = 15). Eight was the cutoff number to define students in Overconfident groups because that was the average number of overconfident responses. Additionally, participants were grouped into three tritiles based on cumulative GPAs, with tritile 3 being the top tier (3.89 to 4.0) and the bottom tier ranging from 2.05 to 3.4.

Functional MRI data were processed and analyzed using the FMRIB Software Library (FSL; Jenkinson, Beckmann, Behrens, Woolrich, & Smith, 2012). Images were corrected for head motion, registered to the T1 image and normalized to the MNI 2mm template. In first level models for each run, we regressed the fMRI signal on task onsets convolved with a double gamma hemodynamic response function. Separate contrasts were performed for error models > baseline; correct models > baseline, and error-containing > correct models. Furthermore, we contrasted trials where students responded they were confident > non-confident trials. Parameters were averaged in fixed effects models and passed to a group analysis conducted with a mixed effects ANOVA. Students' total fMRI task accuracy was covaried in all group comparisons so that any comparison of Calibrated and non-Calibrated groups in their brain activity already accounts for potential group differences in accuracy. Group contrasts were thresholded at a cluster-corrected Z of 3.1 at $p <.05$.

CHAPTER IV

RESULTS

We examined all data distributions to evaluate whether they met statistical assumptions. All data were normally distributed with minimal skew (skewness is from .12 to .57) and kurtosis (kurtosis is from -.75 to -.04). Results for each research question are presented below.

Can life sciences undergraduate students be classified as Calibrated or Non-Calibrated based on performance assessments? (RQ 1)

Behavioral Results from Model Evaluation Task

In general, there was a moderate correlation between total accurate responses and total confident responses ($r = .41$, $p = .02$) (see Figure 2). Figure 3 illustrates students' total accuracy on the model-based fMRI task relative to their total number of reported confident responses based on their calibration groups. For students in the Calibrated group, there was a strong linear association between accuracy and confidence ($r = .91$, $p < .001$), but there was a much less robust relationship for students in the Non-Calibrated group ($r = .22$, $p = .44$).

An independent-samples t-test was conducted to compare both groups' total accuracy and total confident responses, as well as their general academic achievement. The mean accuracy for the students in the Calibrated and Non-Calibrated groups was similar, *M (SD)* = 23.84 (4.46) vs. 23.00 (3.23), $t(32) = -.61$, $p = .54$. Additionally, students in the Non-Calibrated group showed higher confidence than students in the Calibrated group, *M (SD)* = 30.33 (3.77) vs. 24.00 (3.67), $t(32) = 4.94$, $p < .001$. GPA correlated positively with total task accuracy ($r = .43$, $p = .01$), but not with confidence, $r = -.07$, $p = .69$.

Additionally, Figure 4 illustrates that when participants were inaccurate, they tended to be overconfident, as opposed to underconfident, in their responses. Therefore, we conducted additional exploratory analyses that focused on the differences between students who were Overconfident compared to students who were Calibrated/Underconfident. Students in the Overconfident group were less accurate on the model evaluation task than students in the Calibrated/Underconfident groups, $N = 19$, $M (SD) = 21.37 (2.34)$ vs. $N = 15$, $M (SD) = 26.13 (3.98)$, $t(32) = 4.36$, $p < .001$. They also had lower GPAs, $M (SD) = 3.41 (.53)$ vs. $M (SD) = 3.89 (.24)$, $t(32) = 3.22$, $p = .003$.

Do Students in the Calibrated and Non-Calibrated group differ in neural activity? (RQ 2)

Neuroimaging Results from Model Evaluation Task

We conducted separate comparisons of brain activity for correct models and error-containing models relative to baseline (correct models > baseline; error models > baseline). Controlling for students' overall task accuracy, there were no differences in brain activity for students in the Calibrated vs. Non-Calibrated group or students who in the Overconfident vs. Calibrated/Underconfident group. However, task accuracy was associated with stronger activation in the left middle frontal gyrus (158 voxels; BA 10) when evaluating correct models (see Figure 5). Next, we contrasted brain activity for error > correct models. Overall (across the entire sample), students did not show a significant difference in their responses to these different trial types.

We also compared students' brain activity in relation to their confidence judgments. Specifically, we examined the difference in brain activity for confident > non-confident trials. Two students were excluded from this analysis because they reported that they were confident on every trial. In general, students in the Calibrated group showed higher levels of activity in five different brain region clusters for their confident responses. The largest of these clusters was in the anterior cingulate gyrus (254 voxels, BA 32) (see Figure 6).

How does students' calibration relate to academic achievements, such as GPA and to their general cognitive performance? (RQ 3)

To address research question 3, we compared the calibration groups on other measures of behavior, including GPA, general cognitive performance, self-efficacy, and engagement in the modeling task (See Table 2).

Academic Achievement (GPA)

Students in the Calibrated group had a slightly, although not significantly, higher cumulative GPA ($M = 3.71$, $SD = .48$) than students in the Non-Calibrated group ($M = 3.51$, $SD = .49$, $t(32) = -1.15$, $p = .26$). As an additional exploratory analysis, we examined the relationship between students' cumulative GPA and their performance in the model evaluation task. Participants were categorized into three tritiles based on cumulative GPAs, with tritile 3 ranging from 3.89 to 4.0 and the lowest tier ranging from 2.05 to 3.4. In general, for participants in the high tritile ($N = 12$, $M = 27.17$, $SD = 3.33$) total accuracy rates were higher than participants in middle ($N = 10$, $M = 21.25$, $SD = 1.82$) and low tritiles ($N = 12$, $M = 21.70$, $SD = 3.30$, $F(2, 31) = 15.41$, $p < .001$). Additionally, participants in the low tritile ($N = 12$, $M = 27.80$, $SD = 6.41$) were slightly more confident in their responses than those in the middle (*N* =10, *M* = 25.92, *SD* = 4.87) and high tritiles (*N* =12, *M* = 26.83, *SD* = 3.41, $F(2, 31) = .40$, $p = .68$), although this difference was not significant (see Figures 7 and 8).

Cognitive Assessment Results

Participants completed the KBIT-2, which measured both their verbal and non-verbal reasoning skills. One participant did not fully complete a section of the KBIT-2 assessment because of time constraints. Therefore, the standardized score represented 33 participants. On average, participants' combined aggregated standardized score on the assessment was 102.73 (*SD* = 12.17). Students in the Calibrated group had slightly higher, although not significantly higher, standardized scores on the tests (*N* = 19, *M* = 103.32, *SD* = 13.96), than students in the Non-Calibrated group (*M* = 101.93, *SD* = 9.68, $t(31) = -.32$, $p = .75$).

Reported Self-Efficacy Results

Participants completed Baldwin, Ebert-May, and Burns's (1999) that assessed their confidence in completing or performing biology-related tasks. Note that lower scores indicate higher levels of self-efficacy. In general, participants reported that they were "very confident" to "fairly confident" that they could do the specific task (*M* = 2.20, *SD* = .84). Students in the Calibrated group reported slightly less confidence (*M* = 2.35, *SD* = .87) than students in the Non-Calibrated group (*M* = 2.13, *SD* = .79), although this difference was not statistically significant for any individual item or for the mean scores, $t(32) = -.65$, $p = .52$. (Appendix B).

Next, we examined the relation of calibration group to each of the three factor scores for the biology self-efficacy measure. Students in the Non-Calibrated group (*N* =

15, $M = 17.13$, $SD = 4.00$, $t(32) = -1.62$, $p = .12$) reported that they were more confident in in writing and critiquing biological ideas through laboratory reports (Factor 1) than students in the Calibrated group ($N = 19$, $M = 19.63$, $SD = 4.80$), although this difference was not significant. However, the effect size ($d = .56$) for this factor indicated a moderate difference. For Factor 2, students in the Calibrated group ($M = 19.32$, $SD = 4.55$) and students in the Non-Calibrated group ($M = 19.13$, $SD = 5.41$), $t(32) = -.11$, $p = .92$) reported similar confidence ratings. Similarly, for Factor 3, students in the Calibrated group ($M = 12.84$, $SD = 4.40$) and students in the Non-Calibrated group ($M = 12.80$, $SD = 3.97$, $t(32) = -.03$, $p = .98$) reported similar confidence ratings.

Reported Positive Negative Affective Scale Results

Participants completed a Positive and Negative Affective Scale that included 12 items. The Engagement variable was used to determine whether the behavioral and neural results from both the Calibrated and Non-Calibrated groups varied because of different levels of participation or engagement in the fMRI task. With $t(32) = .94$, $p = .36$, there is evidence to suggest that, on average, students in the Calibrated and Non-Calibrated group did not differ in engagement levels during the fMRI task.

CHAPTER V

DISCUSSION

Effective student learning involves accurate self-regulatory and metacognitive skills (Stanton et al., 2015; Zimmerman, 1995). Prior research findings demonstrate that low-performing students are typically less accurate at predicting their academic performance and tend to have lower metacognitive calibration than high-performing students (Hacker et al., 2000; Morphew, 2020). Metacognition is central to science education, because it is critical to developing and cultivating a deep conceptual understanding of scientific concepts (Nielsen et al., 2009). Specifically, in biology education, students with a higher awareness of the learning process and a stronger ability to monitor, regulate, and control learning tend to have a more meaningful understanding of targeted biology concepts and better scientific inquiry skills (Eilam & Reiter, 2014; Martin et al., 2000). It is also likely that these students are also more likely to engage in conceptual change because they are more likely to recognize when there are gaps in their understanding. Likewise, poor metacognitive skills, such as being overconfident, can lead to erroneous decision-making behaviors and false ideas, indicating a lack of either metacognitive awareness of their deficits or ineffective self-regulation skills (Kruger & Dunning, 1999). This study examined the relationships among undergraduate life sciences students' metacognitive calibration, behavioral performance, and brain activity when engaged in reasoning about the accuracy of biological models.

Metacognitive Calibration and Academic Performance

The first primary goal of this study was to determine whether undergraduate biology students can be classified as Calibrated or Non-Calibrated based on performance assessments. The study revealed two distinct groups of students with individual differences. While there was a strong linear association between accuracy and confidence among students in the Calibrated group, there was a moderate and non-significant relationship between accuracy and confidence for students in the Non-Calibrated group. Students in the Calibrated group might be better at recognizing the need for increased effortful or strategic reasoning during trials that demand error detection, which supports Zimmerman's self-regulated learning theory. Additionally, this finding suggested that accurate self-monitoring is a necessary skill for successful learning. For example, behavioral findings revealed that students in the Calibrated and underconfident students had a higher GPA than students in the Non-Calibrated, Overconfident group, and that a higher GPA that correlated with more accurate performances. These findings illustrated and supported the fact that students tend to be inaccurate in predicting their performance, especially when performance is low (Hacker et al., 2000). Judging and monitoring behavior is important in academic settings because strategic thinking leads to effective reasoning, problem-solving, and concept learning. Successful and calibrated students tend to use a variety of self-regulated strategies that help them realize their learning and performance goals, as well as apply their knowledge in novel situations (Stone, 2000; Zimmerman, 2002).

Neural Correlates of Metacognition

No significant differences in neural activity were found between students in the Calibrated and Non-Calibrated groups when they were evaluating models with errors vs. models without errors. Reasons for this finding could include the fact that the analytic sample size of students was relatively small and that these students, regardless of their calibration levels, were highly motivated and fully engaged in biological reasoning (their ratings on the engagement scale were universally quite high), a factor that may erase differences in calibration between the two distinct groups. However, we did find that, when comparing brain activity for trials where students said they were confident relative to not confident, students in the Calibrated group showed higher activity in the anterior cingulate gyrus, superior frontal gyrus, and occipital cortex after controlling for their accuracy. That is, students who are calibrated showed more differentiation in their brain activity for models they later indicated they were confident in relative to those in which they were not confident. Students in the Calibrated group likely tended to activate the ACC during the trials largely because they feel more confident in effortful error-detection processes. On the other hand, students in the Non-Calibrated group seemed to show less discrimination. These non-discriminating neural pattern findings support the indicators for their non-calibrated behavior. There is limited research on how the neural correlates of how metacognition calibration affects academic performance; however, these findings of differences in calibrated vs. non-calibrated students' recruitment of frontal regions support Fleming and Dolan's (2012) work showing that the lateral PFC is important for the accuracy of retrospective judgments of performance.

Although there were no differences in brain activity for students in the Calibrated vs. Non-Calibrated group for model based trials as a whole, task accuracy, in general, was associated with stronger activation in the left middle frontal gyrus when evaluating correct models. Consistent with the self-regulated learning theory, these findings suggest that, regardless of how calibrated students are, if they are more accurate, they tend to show more PFC activity. Students with higher accuracy may be better at recognizing the need for increased effortful or strategic reasoning during trials that demand error detection and therefore deploy PFC during these trials, similar to what science experts do (Masson et al., 2014).

Students' Self-Efficacy

Self-efficacy is a vital construct because it explains students' behaviors toward learning, as well as predicts academic performance (Schunk, 1989). In general, students in the Calibrated and Non-Calibrated groups did not differ in response to the self-efficacy questionnaire. A factor as to why students with different patterns of calibration accuracy did not seem to differ in their levels of self-efficacy might be because the self-efficacy questionnaire focused solely on topics related to biology, which was the college major for most of these students. In other words, the questionnaire focused on biology and not on the broader area of self-efficacy in general. Another reason might be an ambiguous relationship between self-efficacy and the separate, but related, concept of self-esteem. More research might reveal that these two concepts of self-efficacy and self-esteem are less differentiated in student attitudes than is suggested by past empirical studies.

Our findings contradict previous literature, which suggests that self-efficacy contributes to academic performance because it influences and modifies human behavior (Bandura, 1977). Students who have a low sense of self-efficacy tend to harbor negative thoughts and, therefore, set low goals for themselves. While extensive evidence has proven the effects of self-efficacy on students' academic accomplishments (Schunk, 1989; Bandura, 1997; Chemens et al. 2001), we do not fully understand whether self-confidence is a primary cause of academic success or whether that success is rooted more in the students' efforts and skills (Yusuf, 2011). What the findings of the current study suggest is that calibration accuracy is not necessarily linked to self-efficacy and that students whose confidence and accuracy are better matched are not necessarily the ones with higher self-efficacy. Therefore, a full understanding of how individual differences in self-regulation drive student success may require an evaluation of both constructs, as they both may have relatively independent effects.

In this study, the self-efficacy questionnaire focused solely on students' confidence in completing or performing biology-related tasks and not on overall self-efficacy. Developing a healthy sense of self-efficacy is especially important in addressing challenging subjects, including life science and biology. As course material becomes more complex and demanding, students' efficacy becomes an important construct that influences the potential for learning (Baldwin, Ebert-May & Burns, 1999. Future research on self-efficacy should include a focus on how metacognition calibration affects student achievement in biology and biology-related courses.

Relation between Metacognition, General Cognition, and Learning

In general, metacognition is a broad factor that helps explain how individuals monitor, judge, and regulate their behaviors (Gomes, Golino & Menezes, 2014; Winne, 1996). Research suggests that both intelligence and metacognition play a role in determining or predicting academic performance (Meijer, Veenman & van Hout-Wolters, 2012). Specifically, metacognition and intelligence contribute positively to learning results (Veenman, Elshout & Meijer, 1997; Veenman & Verheij, 2003; Veenman, Wilhelm, & Beishuizen, 2004). In this study, students' standardized score on the cognitive assessment in the Calibrated group was slightly higher than students in the Non-Calibrated group, though difference was not statistically significant. However, the

KBIT-2 assessment is not a comprehensive assessment of intelligence and was intended mainly to get a general indication of students' general reasoning. The results, nonetheless, accord well with other literature showing that metacognition is not dependent on students' general cognitive performance.

How researchers operationalize intelligence and, particularly, metacognition determines the strength of the relationship. For example, Flavell (1979) noted that there are different levels of metacognition, including how individuals plan, monitor, and evaluate their performance. Flavell also distinguished between metacognitive knowledge, metacognitive experiences, goals or tasks, and actions or strategies. Whereas Veenman (1993) stressed that the most important distinction of metacognition is metacognitive knowledge and metacognitive skill. Moreover, Zimmerman (1986) viewed students' learning process in three defined phases— forethought, performance, and self-reflection—which highlights how goals and strategic planning guide academic performance. On the other hand, intelligence is typically measured by assessing vocabulary, verbal analogies, linear syllogisms, number series and speed, as well as embedded figures (Meijer, Veenman & van Hout-Wolters, 2012).

To assess fluid intelligence, ratings of self-confidence, and self-evaluation as measures of metacognition among undergraduate students, Stankov (2000) used a computerized version of the standard and the advanced forms of Raven's Progressive Matrices where participants were also required to express their confidence that their answer was correct. Findings from their study demonstrated substantial correlations between non-verbal intelligence and (a) measures of self-confidence and (b) self-evaluation. His work also suggested that self-confidence might be an aspect of a metacognition (e.g., self-monitoring), and that self-confidence should be thought of as "residing somewhere on the borderline between personality and intelligence" (p. 141). As self-monitoring and self-evaluation skills help students' success levels, metacognitive processes are also reinforced.

Limitations and Directions for Future Research

This study was not without its limitations. One of the significant limitations was that one life science task is not necessarily indicative of overall academic performance or general metacognitive abilities. Additional assessments would be beneficial for determining and evaluating the neural and behavioral effects of metacognitive processes, as well as for determining whether metacognitive calibration accuracy is a "trait-like" characteristic or whether it is more content-specific. Specifically in this study, another potential limitation was the absence of measurements of the participants' levels of attention and motivation during the task. Future studies should further investigate and measure how attention and motivation levels, as well as other individual factors, impact metacognition skills and their relation to brain activation during essential learning tasks. Other limitations here included a disproportionate representation of females and Euro-American Whites, as well as a small range in GPAs. Lastly, this study was conducted at a Midwestern university in the United States, which limits generalizability.

Potential future research is needed to determine whether self-regulated learners are more calibrated. In other words, to what extent can calibration accuracy predict academic achievement? Understanding this direction may also have important implications for instructional design. Likewise, future research would also examine how students might be encouraged to reflect on their calibration accuracy and whether such reflection might aid in the process of conceptual change in science. Lastly, potential future research is needed to determine how metacognition calibration affects students' learning and academic performance throughout their educational trajectory.

Conclusion

Metacognitive calibration, a metacognitive monitoring skill, refers to students' ability to monitor their task performance (Crane et al., 2017). For example, when students can effectively monitor their performance, they can adjust their effort and strategies for subsequent performances. The concept of calibration typically refers to the accuracy of learners' perceptions of their performances (Pieschl, 2009) or, in other words, how aware they are of their internal processes (Stone, 2000). Most research on metacognition is concerned with how individuals monitor their progress during learning. Few neuroimaging studies focus on the neuroscientific framework of error detection, which suggests the need for investigating a possible link between students' metacognition calibration skills and their academic performance.

This thesis aimed to determine whether undergraduate life sciences students who demonstrated more calibrated self-assessments of their task performance would also demonstrate higher activity in the lateral prefrontal and anterior cingulate brain regions. Behavioral findings in this study supported previous research that indicates that more calibrated students are better at practicing self-regulation skills, such as self-monitoring and accurately assess their confidence in their own knowledge. Additionally, students in the Calibrated group showed higher activity in the anterior cingulate gyrus, superior frontal gyrus and occipital cortex after controlling for their accuracy when comparing brain activity for trials when they reported they were confident relative to not confident.

The results of this thesis have important educational implications. First, these findings stress the need to foster and nurture metacognition and self-awareness in the classroom. Students who are more self-aware and calibrated are typically more adaptable to the demands of learning because they are consistently more accurate in their self-monitoring (Zimmerman, 1995). Having effective self-regulatory and metacognitive awareness can help students continually to update and modify their knowledge, allowing for conceptual change to occur. Additionally, instructors could provide opportunities for students to reflect on their coursework by focusing on the learning process rather than exclusively on the content or outcomes themselves, thereby engaging students in reflexive and adaptive thinking. Instructors may also provide direct and immediate feedback, a core mechanism of self-regulated learning that positively impacts academic achievement (Butler & Winne, 1995). In other words, feedback has the power to help guide students' learning by providing explanations and rationales as to whether they were correct, which allows students to know what they know or what they do not know. Ultimately, students who learn and engage in metacognitive skills tend to be more aware of their thinking and are, therefore, more likely to be both active and more fully participant in their learning.

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Table 1

Demographics of the Calibration Groups

Demographics

	Calibrated		Non-Calibrated	
	N	%	N	%
Gender				
Female	18	59.94	11	32.35
Male	1	2.94	4	11.76
Race and Ethnicity				
European American/White	17	50.00	14	41.17
Hispanic American/Latino	2	5.88	0	0.00
Asian/Asian American	1	2.94	1	2.94
Grade Level				
Freshman	15	44.12	11	32.35
Sophomore	3	8.82	3	8.82
Junior	1	2.94	1	2.94

Note. Percentages may not add up to 100 percent because of multi-select questions.

Table 2

Sample Descriptive Statistics for the Calibration Groups

	Calibrated (*n* = 19)		Non-Calibrated (*n* = 15)			
	M	*SD*	*M*	*SD*	*t*	*p*
Cumulative GPA	3.71	.48	3.51	.49	-1.15	.26
KBIT-2	103.32	13.96	101.93	9.68	-.32	.75
Self-Efficacy	2.35	.87	2.13	.79	-.65	.52
Factor 1	19.63	4.80	17.33	4.00	-1.62	.12
Factor 2	19.32	4.55	19.13	5.41	-.11	.92
Factor 3	12.84	4.40	12.80	3.97	-.03	.98
Engagement	16.00	2.05	16.60	1.55	.94	.36

Figure 1

Layout of the Model Evaluation Task Presented in the fMRI

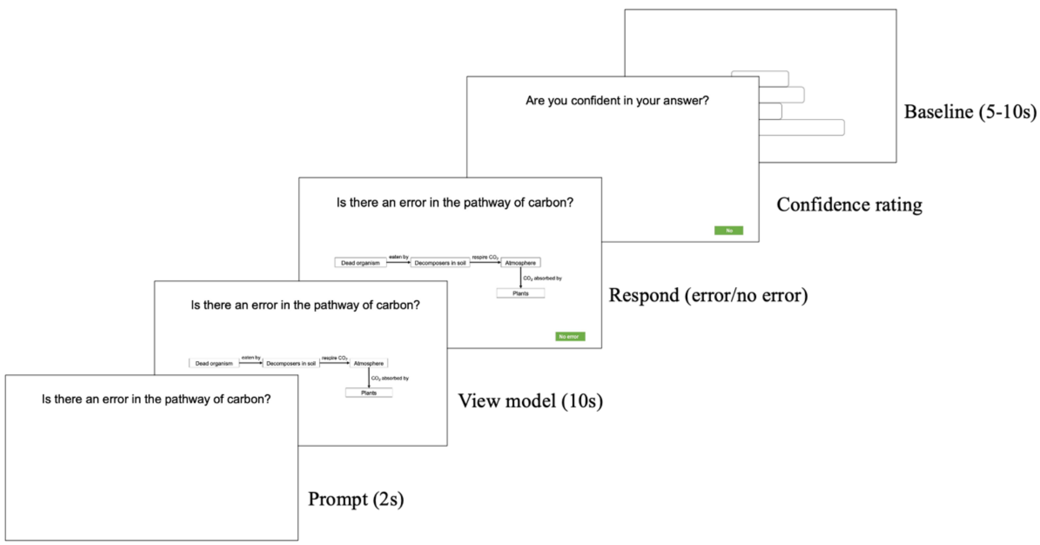

Figure 1: The model evaluation task required participants to examine and determine whether the presented biology models contained errors, as well as to assess their confidence level for each model.

Figure 2

Total Accurate Responses to Total Confident Responses

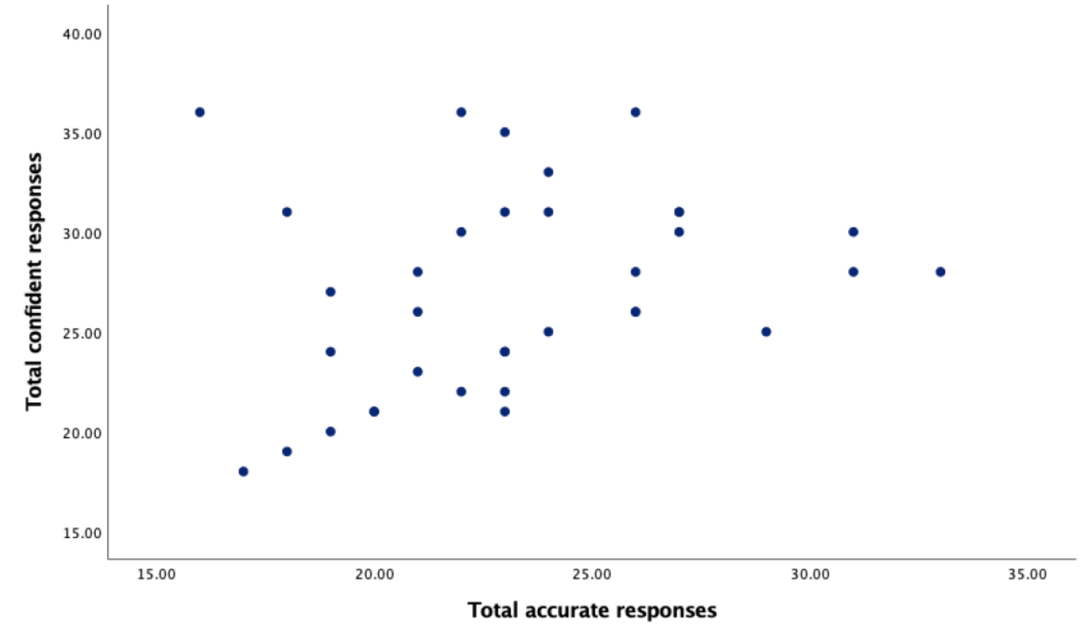

Figure 2: Correlation between students' total accuracy and reported confidence.

Figure 3

Calibration Groups

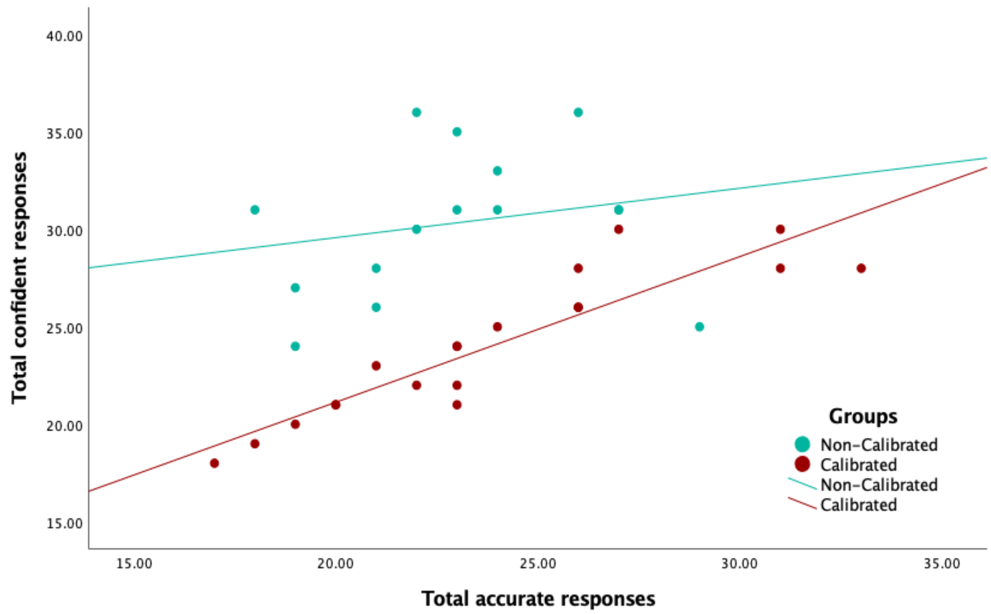

Figure 3: The relationship between total accuracy and their total number of reported confident responses levels based on students' calibration groups during the model evaluation task.

Figure 4

Accurate Trials to Students' Confidence Ratings

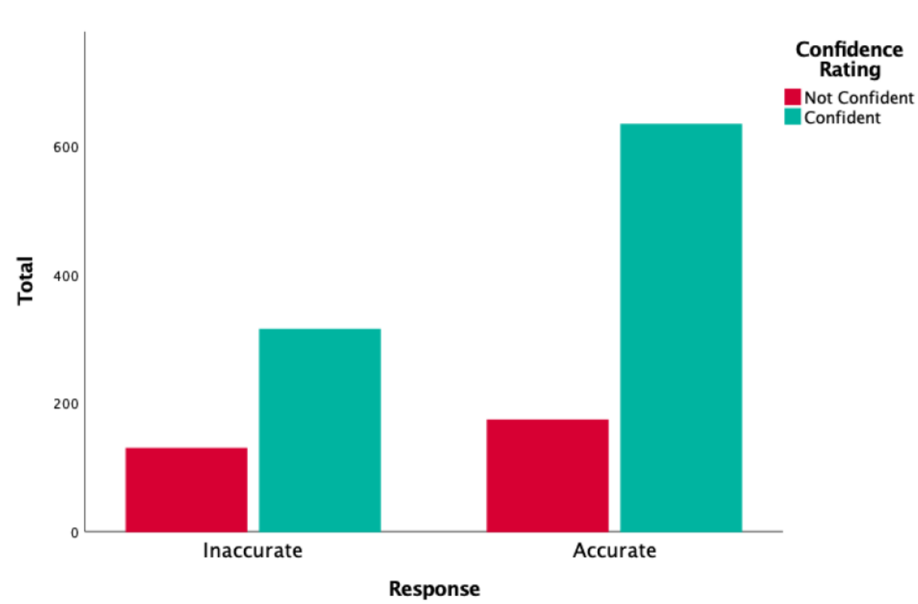

Figure 4: Accurate trials in relation to students' confidence ratings for the model evaluation task.

Figure 5

Students' Neural Activity When Evaluating Correct Models

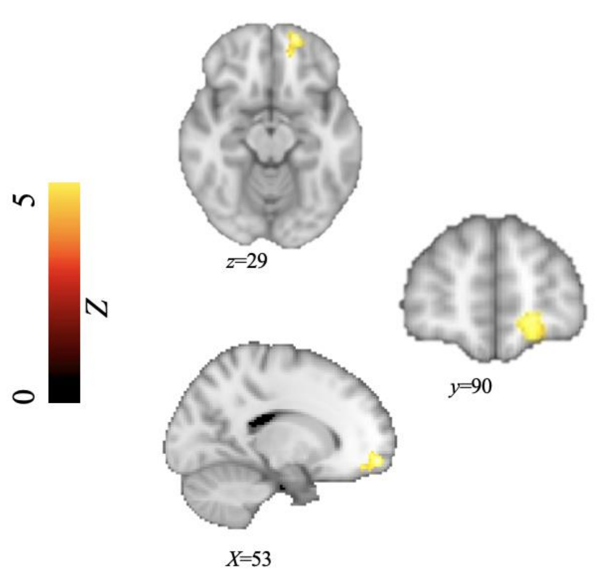

Figure 5: Accuracy during the model evaluation task was associated with stronger activation in the left middle frontal gyrus when evaluating correct models.

Figure 6

Calibrated Group's Neural Activity While Making Confidence Judgments

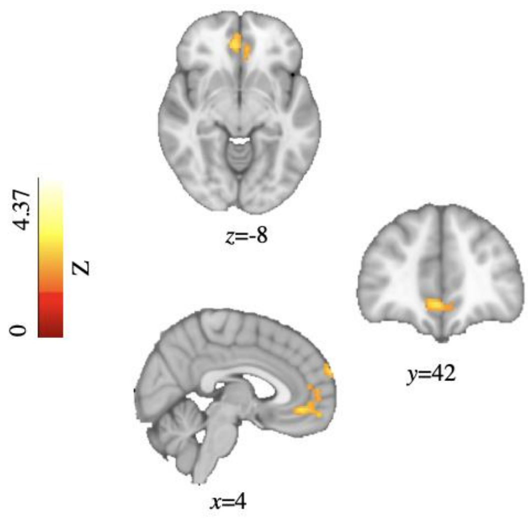

Figure 6: Students in the Calibrated group showed higher levels of activity in the anterior cingulate gyrus on trials they were confident on in the model evaluation task than students in the Non-Calibrated group.

Figure 7

Total Number of Accurate Responses by Tritiles

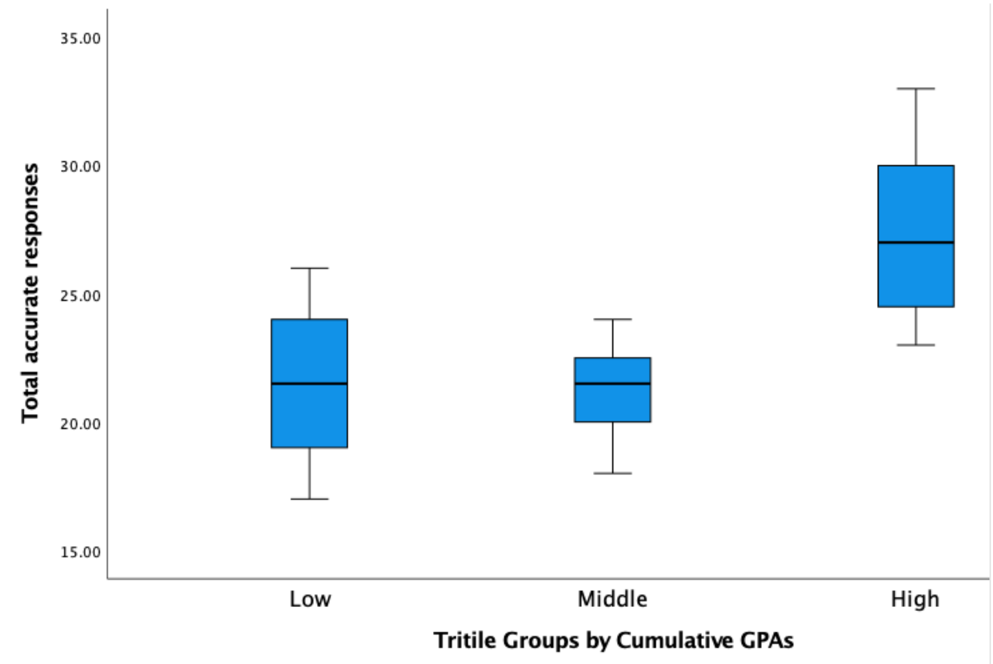

Figure 7: Total accuracy rates for participants with low, middle, and high GPA levels.

Figure 8

Total Number of Confident Responses by Tritiles

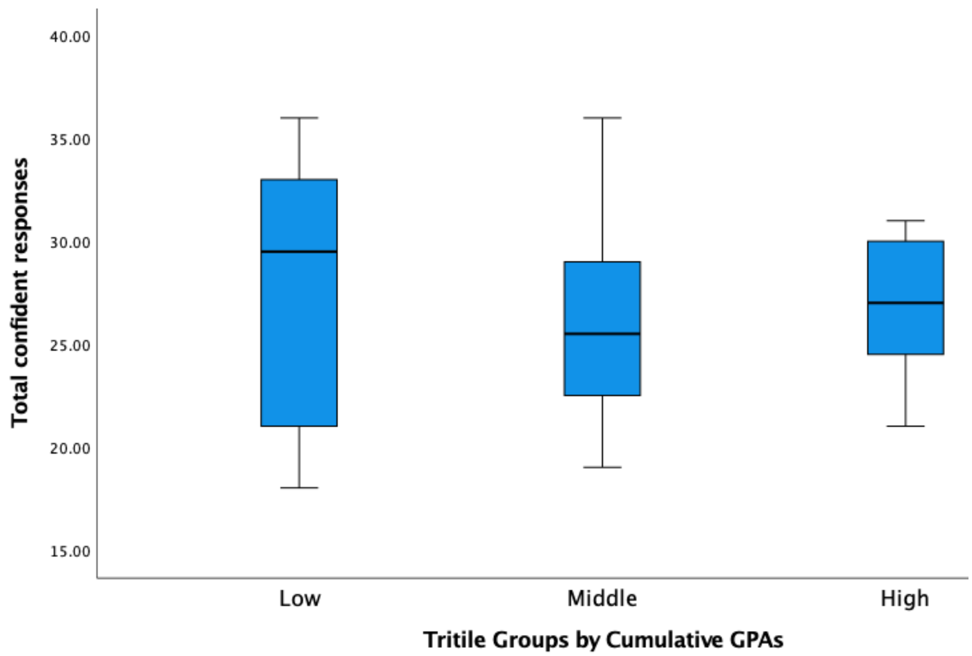

Figure 8: Total confident rates for participants with low, middle, and high GPA levels.

APPENDIX A

Modified PNAS Engagement Assessment

The scale consists of a number of words that describe different feelings or emotions. Read each item and list the number from the scale below next to each word. Indicate to what extent you felt this way today while you were completing the modeling/fMRI activities.

1	2	3	4	5
Very slightly or not at all	A little	Moderately	Quite a bit	Extremely

___________Interested

___________Motivated

___________Distressed

___________Enthusiastic

___________Proud

____________Irritable

____________Alert

____________Inspired

____________Nervous

____________Ashamed

____________Determined

____________Attentive

APPENDIX B

Calibrated and Non-Calibrated Students' Self-Efficacy in Biology

	Calibrated	Non-Calibrated	Total
	M (SD)	*M (SD)*	*M (SD)*
How confident are you that after reading an article about a biology experiment, you could write a summary of its main points?	2.00 (.82)	1.93 (.71)	1.97 (.76)
How confident are you that you could critique a laboratory report written by another student?	2.58 (.96)	2.00 (.66)	2.32 (.88)
How confident are you that you could write an introduction to a lab report?	2.16 (1.01)	1.80 (.68)	2.00 (.89)
How confident are you that after reading an article about a biology experiment, you could explain its main ideas to another person?	2.00 (.75)	2.13 (.74)	2.06 (.74)
How confident are you that you could read the procedures for an experiment and feel sure about conducting the experiment on your own?	2.63 (.83)	2.47 (.64)	2.56 (.75)
How confident are you that you could write the methods section of a lab report (i.e., describe the experimental procedures)?	2.26 (.93)	2.00 (.66)	2.15 (.82)
How confident are you that after watching a television documentary dealing with some aspect of biology, you could write a summary of its main points?	2.21 (1.03)	2.07 (.88)	2.15 (.96)
How confident are you that you will be successful in this biology course?	1.50 (.62)	1.73 (.59)	1.61 (.61)
How confident are you that you could write up the results to a lab report?	1.89 (.74)	2.00 (.76)	1.94 (.74)

How confident are you that after watching a television documentary dealing with some aspect of biology, you could explain its main ideas to another person?	2.00 (.82)	1.93 (.88)	1.97 (.83)
How confident are you that you will be successful in another biology course?	1.68 (.58)	2.00 (.93)	1.82 (.76)
How confident are you that you could write the conclusion to a lab report?	2.26 (.65)	1.80 (.56)	2.06 (.65)
How confident are you that after listening to a public lecture regarding some biology topic, you could write a summary of its main points?	2.42 (1.07)	2.40 (.83)	2.41 (.96)
How confident are you that you would be successful in an ecology course?	2.63 (.96)	2.40 (1.06)	2.53 (.99)
How confident are you that you could analyze a set of data (i.e., look at the relationships between variables)?	2.21 (.98)	2.20 (.68)	2.21 (.85)
How confident are you that after listening to a public lecture regarding some biology topic, you could explain its main ideas to another person?	2.21 (.92)	2.33 (.90)	2.26 (.90)
How confident are you that you would be successful in a human physiology course?	1.89 (.74)	2.33 (1.05)	2.09 (.90)
How confident are you that you could tutor another student on how to write a lab report?	3.00 (.94)	2.40 (.91)	2.74 (.96)
How confident are you that you could critique an experiment described in a biology textbook (i.e., list the strengths and weaknesses)?	2.84 (.83)	2.67 (.72)	2.76 (.78)
How confident are you that you could tutor another student for this biology course?	2.63 (1.07)	2.40 (.99)	2.53 (1.02)

How confident are you that you could ask a meaningful question that could be answered experimentally?	2.37 (.76)	2.13 (.83)	2.26 (.79)
How confident are you that you could explain something that you learned in this biology course to another person?	2.11 (.94)	1.93 (.80)	2.03 (.87)
How confident are you that you could use a scientific approach to solve a problem at home?	2.37 (1.01)	2.00 (.76)	2.21 (.91)