Comparison of Brain and Behavioral Measures During a 3D-Computer Maze Task in Order to Examine the Learning Process

by

Nicole Gomes

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Honors Bachelor of Science in Exercise Science with Distinction

Spring 2015

Comparison of Brain and Behavioral Measures During a 3D-Computer Maze Task in Order to Examine the Learning Process

by

Nicole Gomes

Approved: _____
Dr. Nancy Getchell, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: _____
Dr. Michele Lobo, Ph.D.
Committee member from the Department of Physical Therapy

Approved: _____
Dr. Elizabeth M. Orsega-Smith, Ph.D.
Committee member from the Board of Senior Thesis Readers

Approved: _____
Michael Arnold, Ph.D.
Directory, University Honors Program

ACKNOWLEDGMENTS

I would first like to thank Dr. Nancy Getchell, my thesis director. I want to thank her for encouraging me to get involved in research, and for guiding me and supporting me along the way. I want to thank her for believing in me, when I was just about ready to give up. I could not have made it through the thesis process successfully without her. I would also like to thank Dr. Lynn Liang, the graduate assistant in our lab. Lynn was always there to answer my questions, and to help me move forward when I got stuck. Lynn is another person who allowed me to successfully complete my thesis. Additionally, I would like to thank my second reader, Dr. Michele Lobo, and my third reader, Dr. Elizabeth M. Orsega-Smith, for helping me and providing suggestions throughout the thesis process, and for being so understanding when our project had to change. Thank you to Dr. Patricia Shewokis of Drexel University for coming to visit our lab to give us guidance based upon her experience with fNIRS and MazeSuite. Thank you to Dr. Hasan Ayaz, also of Drexel University, for always having a solution to our MazeSuite problems, and for answering every question in each of the countless emails that we sent. Furthermore, I would like to thank my lab-mates, Autumn, Sarah, Tim, Alex, and Emily, for our great teamwork in the lab. I would also like to thank everyone who tested mazes along the way, as this was an essential step before our final data collection. Finally, thank you to my friends and family who supported me throughout this yearlong process.

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Motor learning is a "set of processes associated with practice or experience leading to relatively permanent gains in the capability for skilled performance." A performance curve can be used to chart performance progress on a task, to ultimately infer learning of the skill. The prefrontal cortex of the brain is highly involved in motor learning, as it is controls conscious executive functions such as planning and decision-making. As learning progresses, a skill requires less conscious control and the prefrontal cortex becomes less involved in movement execution. The fNIRS device, which emits infrared light, is worn on the forehead and can indirectly measure brain activity. The purpose of this study is to investigate the link between brain and behavioral measures during a cognitive-motor task. Three participants, ages 18-22, completed either 10 or 20 trials of a 3D-computer maze constructed in the program MazeSuite (number of trials depended on their success with the task). Throughout the task, levels of oxygenated hemoglobin in the prefrontal cortex were measured as the brain measure. Path length was measured as the behavioral measures. Our results showed that in general, path length decreases as trial number increased. This demonstrates that the participants learned the maze. For two of the three participants, oxygenated hemoglobin also decreased as path length increased. This indicates a decrease in prefrontal cortex activity as the task became better learned. The relationship between path length and oxygenated hemoglobin was not consistent among participants. More participants, and the use of more advanced statistics are necessary to draw more accurate conclusions from this data. Additionally, future

studies can further this research by using this experimental protocol to study the contextual interference effect, as well as differences in brain activity between adults, typically developing children, and children with disabilities.

Chapter 1

Introduction

1.1 Motor Learning

Motor learning is defined as a "set of processes associated with practice or experience leading to relatively permanent gains in the capability for skilled performance"(1). Motor learning can be identified as a series of stages, which describe learner characteristics as they progress from early to late learning during the acquisition of a skill. Fitts and Posner developed a learning-stage model that focuses on perceptual-motor learning and how cognitive processes change during the learning process. Stage one in Fitts and Posner's model is called the cognitive stage, which represents early learning. In this stage, the learner attempts to determine the goal of the skill and figure out what to do, when to do it, and how to do it. Providing instructions and demonstrations helps the learner to understand the skill. During early learning rapid gains in skill performance are observed, but performance appears uncertain and poorly timed. Learners may use self-talk to guide themselves through the newly learned action. This stage is highly cognitive, as skills require a lot of attention and planning (2).

Stage two, middle learning, is called the fixation stage, alternatively known as the association or motor stage. During this stage many of the initial cognitive steps of the skill such as how to perform it have been learned. The learner now focuses on performing the skill more effectively and using feedback to correct his/her actions. Performance continues to improve steadily as a motor program is developed and

performance is more efficient. However, there is still inconsistency among trials because the learner is trying to discover the most efficient way to perform the skill. While self-talk was important in stage one, it is greatly reduced here, as the learner now knows the steps of the skill(2).

Stage three, late learning, is called the autonomous stage. This stage is reached after the learner has gone through a great deal of practice. Skills seem to be performed with automaticity. In this stage, the skill requires much less attention demand, so the learner can now focus on strategies. Here, performance is consistent and improvements are very slow, often undetectable, because the learner has already mastered the skill. Accordingly, self-talk is absent. Despite the lack of performance improvements, learning is still occurring in the autonomous stage (2).

1.2 Performance Curves

Performance curves are the most common method used to assess the learning process (1). To produce a learning curve, the performance measure from each trial is plotted against the trial number so that a trend in the performance measure can be analyzed. Performance curves have a typical shape, as performance gains follow the law of practice. This law states that performance gains are rapid at first and then much slower later. This is displayed on a learning curve, as the curve is steep at first, and more gradual later (see figure 1). While this is the general form, the curve can increase or decrease with practice, depending on the performance measure. For example, if the performance measure increases with practice, the curve is also increasing. While performance curves chart changes in performance over time, they do not chart learning progress (1). It can be interpreted that better performance implies the skill is better

learned, but this cannot be confirmed without later testing skill retention or transfer (1, 2).

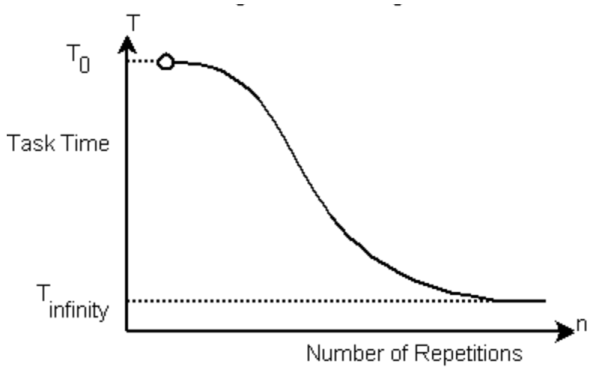

Figure 1: A performance curve tracking a dependent measure that decreases with practice. The shape of this learning curve follows the law of practice (3) .

1.3 The Prefrontal Cortex

The prefrontal cortex (PFC) is the region of the brain located just anterior to the supplementary motor area and the premotor cortex (see figure 2) (4). It is a large section of the brain, occupying about one third of the cerebral cortex (4) . Thus, compared to that of other animals, the human PFC is much larger, which suggests that it may contribute to the high-level cognitive function of humans (5) . These high-level cognitive functions, known as executive functions, allow the PFC to control "'lower-level' cognitive processes and goal-directed, future-oriented behavior" (6) . Other functions of the PFC include language, reasoning, social interactions, creativity, attention, working memory, planning, and decision-making (4, 5) . These processes that occur in the PFC are conscious processes, as they require thought and attention (7) Additionally, the PFC is necessary for intricate motor learning and motor control (8).

Further research has confirmed that the PFC is important for high-level cognitive function, stating that it is the "central executive" of the brain (5, 9) . A lot of this evidence stems from observations of patients with prefrontal cortex damage. Almost every observed case of PFC damage coincides with a loss of executive function, confirming the key role of the PFC in this type of processing (6) . This study will focus on the planning and decision-making functions of the PFC.

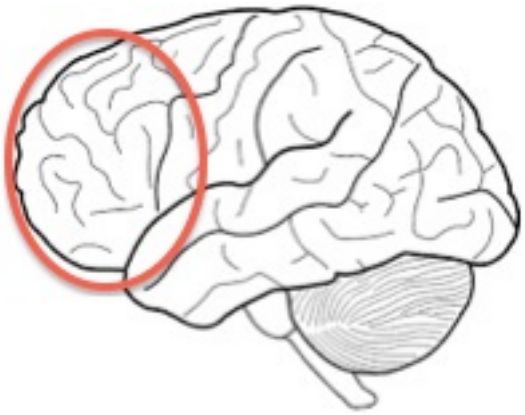

Figure 2: Location of the prefrontal cortex in the human brain. The prefrontal cortex is the circled region.

According to Miller et al., The PFC is not involved in bottom down processing, which controls simple automatic behaviors such as the natural response to turn your head when you hear a sound (10) . Instead, it plays a pivotal role in top-down processing, behavior that must be somehow guided internally. When there are many choices or decisions to make, the goal of the action and the method of achieving it must be identified by the PFC, allowing the person to make the "task-relevant response" (10) . Research has shown the PFC's role in this decision-making process.

The Stroop Test asks individuals to either read the name of a color, or state the color in which the color-word is written in. Patients with impairment in the PFC have difficulties with this task, which demonstrates the key role of the PFC in deciding on the most appropriate response for a given situation (10) . The PFC participates in this cognitive control because it maintains activity patterns that represent goals and the means to achieve them (10) .

The PFC is able to function as a central executive, and cognitive control center, because of its high degree of connectivity in the brain. It has connections with external information, including almost all of the brain's sensory systems, as well as the motor systems and many subcortical structures (5, 10) . It also has connections with internal information, coming from the limbic system and the midbrain, which control memory and reward (5) . Because the PFC has so many sources of input, it is able to implement abstract behaviors, such as planning and decision-making, that require an ability to piece together a great deal of both internal and external information (4) .

While the PFC is essential for early learning, activity in this brain region is diminished in later stages of learning. The PFC is one of the brain's higher association areas. These areas are very active in the early phases of learning when working memory, planning, and decision-making are needed in order to execute the skill. As the skill becomes better learned, the learner no longer needs to consciously think about his/her actions. Thus, these higher-order association areas have reduced activity, and the subcortical pathways begin to take control of the movement. By the later stages of learning the higher association areas, including the PFC are almost completely uninvolved in skill execution. The subcortical pathways control the entire movement (11) . A study by Gentili et al. demonstrated this phenomenon. This study examined

the changes in brain hemodynamics during a cognitive-motor learning task. The highest oxygenation values were seen during early learning, and then HBo progressively reduced. These results demonstrated that there was an initial use of prefrontal cortex executive functioning, followed by a de-recruitment of the same region over time (12).

1.4 Functional Near Infrared Spectroscopy (fNIRS)

Functional near infrared spectroscopy (fNIRS) is an indirect optical brain imaging technique (13) . This technique uses infrared light to study changes in the human brain because near-infrared light is able to penetrate bone and biological tissue (14-16) . The "optical window" for near-infrared light that is absorbed by the brain tissue is 700-1000 nanometers (14). The fNIRS device contains light sources, which shine light onto the scalp and light detectors, which detect the light as it exits the head (8, 16, 17) . The two dominant chromophores (light absorbing molecules) that fall within the optimal fNIRS wavelengths are oxygenated hemoglobin (HBo) and deoxygenated hemoglobin (HBr), which are relevant event markers for brain activity (16, 17) . The device measures the absorption spectra of these two molecules in the blood of the analyzed brain region, which absorb different wavelengths of light (8, 16) . Changes in light levels are interpreted as changes in HBo and HBr levels (8, 16) . By using two different wavelengths of light at the same time, separation of the absorption spectra of HBo and HBr is possible, which allows us to examine changes in levels of both of these molecules (17) . Thus, these devices are able to monitor the hemodynamic response to brain activation by measuring the absorption of light by HBo and HBr (8, 16) . In response to a stimulus, neural activation begins in the individual neurons, as electrical signals move between cells, which changes the

metabolic demands of the cells. This causes an increase in oxygen delivery, oxygen consumption, and cerebral blood flow (16) . In adults, this leads to a typically observed response seen in many research studies: an increase in HBo, an increase in cerebral blood flow (represented by total hemoglobin), and a decrease in HBr (8, 15-17) . The changes in HBo and HBr during response to a stimulus are shown in figure 3. It has been observed that there is a tight coupling between the hemodynamic response, and neural activation, so these changes in HBo and HBr are interpreted as changes in brain activation in the brain region monitored by the fNIRS device (8) . In our study, we will use the fNIRS device to monitor changes in neural activation in the PFC. Ultimately, fNIRS will allow the examination of connections between brain activity and behavioral responses (16) .

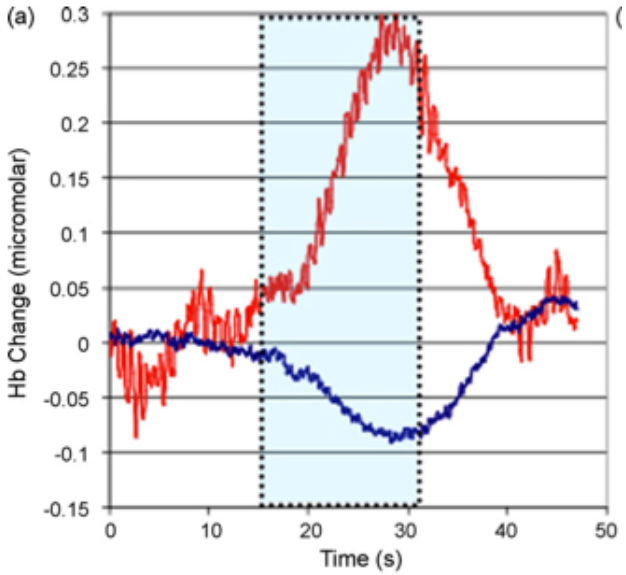

Figure 3: Typical hemodynamic response demonstrating an increase in HBo (red) and a decrease in HBr (blue) during brain activation (16) .

There are several advantages to using the fNIRS device over other traditional brain analysis devices such as fMRI, CT, PET, or EEG. fNIRS uses near-infrared light, which is non-ionizing, so there is no limit to the number of scans one can undergo (17) . The fNIRS device is also inexpensive and portable, so it accessible for researchers, and could be used to perform studies outside of the laboratory. It is also able to accommodate a certain degree of movement, unlike traditional MRI devices used to analyze brain activity (8, 16) . These features make fNIRS a valuable technology that can be used to study brain activity during motor tasks, as it does not require the participant to remain completely still. This feature also makes fNIRS suitable for research on infants, children, or those with movement disorders, who often have trouble remaining still for long periods of time (16, 17). Another important feature of fNIRS is that it is non-invasive (8) , allowing for an indirect but easy viewing of brain activity. Finally, while fMRI is able to provide information about the hemodynamic response, it can only measure HBr. fNIRS is able to measure HBo, total hemoglobin and HBr, providing a more complete picture of the hemodynamic response during neural activation (8) .

1.5 MazeSuite

Maze tasks have often been used to study perceptual motor abilities, as navigating through the world with visual-spatial information is a part of everyday human life (18) . Several studies have found maze learning to be an accurate indicator of changes in the frontal lobe (18) . A study by VanHorn et al found that during initial trials on a maze task there was high blood flow and brain activity in the prefrontal cortex as measured by PET scans. However, after, training and practice on the maze, activation was much lower in the prefrontal cortex, and much higher in posterior brain

regions (18) . This data supports the neuroanatomical concept that during early learning, the prefrontal cortex is more involved for decision-making and feedback processing. As learning occurs, working memory is no longer needed to complete the task, and thus the prefrontal cortex drops its role in the task (18) . Thus, this experiment demonstrates that mazes are an appropriate paradigm with which to study learning.

MazeSuite, developed by Hasan Ayaz at Drexel University, is a program that allows one to create, present, and analyze 3D-computer mazes (13). MazeSuite has an advantage over other programs that can be used to analyze visual-cognitive skills in 3D-environments. It is user-friendly and does not require the operator to learn coding language for the program (19) . There are three main parts of the program. MazeMaker is used to construct mazes. MazeWalker is used to walk through the maze. MazeAnalyzer allows for analysis and path viewing. It tracks behavioral measures such as maze completion time, maze path length, and walking velocity (13). It can also be synchronized with other programs to analyze physiological and neurological changes while completing the perceptual-motor maze task (13). fNIRS, and its data-processing system COBI, work well with the MazeSuite program. Thus, the MazeSuite program, combined with fNIRS, facilitates the examination of connections between brain activity and behavioral responses, which is the goal of our study.

Chapter 2

Methodology

2.1 Phase 1- Mastering fNIRS

In order to move forward with our project, we first had to master the use of the fNIRS device and COBI studio, the data recording software. We began by assisting with data collection on a pilot study in the laboratory, in order to practice using the device. Through our practice we were able to become oriented with the device, learn how to collect and record data, and most importantly, how to set up an experiment for each individual participant. As part of the laboratory's pilot studies, we performed several experiments to test the effects of ambient light on the fNIRS results. By testing participants in a resting state with both the lights on and the lights off, we found that higher values of light absorption were recorded if the lights were on. Thus, to produce the most accurate data, we decided to include turning the lights off in our fNIRS data collection protocol. Collecting pilot data also allowed us to practice refining the data to analyze it. We learned how to mark blocks (trials) on the fNIRS data to separate each trial into its own data file. We also developed the method to process data for our experiment. First, we averaged the values from all 16 channels over the trial. Then, we took the average of each channel's average in order to get a single HBo value for that trial. To collect data, the fNIRS device must be correctly aligned on the participant's head and in full contact with the skin (see figure 4). We quickly learned that it is important to also have some type of cover over the device in order to keep it tight around the participant's forehead. We used a winter ear-warmer as our cover. Another

factor that affects the values obtained from the fNIRS data is the gain, or the power of the light. The COBI manual explains that the values displayed on the screen during data collection must be in between 400 and 4000 millivolts. The initial values differ based upon the participant, and we learned that this could be adjusted by changing the gain in the device settings. Practice with these settings allowed us to learn the parameters for changing the gain, so that we could easily adjust it during our experimental data collection. Through many of these initial practice sessions, we had problems finding the location of the saved data on the computer. With practice, we learned that the data does not save in an easily recognizable format unless you start a new experiment in the COBI program each time. This is another step that we added to our data collection protocol. Through pilot study data collection, we also learned that the participant should be seated in a stationary chair, and should limit his/her head movements. To observe the affects of motion, we had participants shake their head, and rock the chair, while wearing the fNIRS device. While the fNIRS device could accommodate a certain degree of motion, the results were most accurate when the person remained still. Thus, we replaced our rolling and reclining chair with a stationary chair for all further data collection. We also reminded the participant to keep their head still at the beginning of all data collection sessions. A last obstacle we encountered with COBI studio was the event marker settings. Event markers are used to denote where a trial starts and stops in the data from the fNIRS device. Originally, we used manual event markers, which requires the researcher to click for an event marker each time a trial begins and ends. As we began our preliminary experimental data collection, we learned of the automatic event marker settings. Using a cord to link the computer running MazeSuite to the computer running COBI and fNIRS, event

markers can be automatically transmitted. This allows for more efficient data collection, so we began to use automatic event markers. However, when we analyzed the data, we discovered that the event markers were not labeled in recognizable format, and were not always displayed at the correct time. Due to these issues, we had to return to using manual event markers for our final data collection. Through our laboratory's pilot study and our data preliminary experimental data collection, we learned the details necessary to lead our own study using the fNIRS device and COBI studio. Before beginning our final data collection, we completed a proficiency exam, conducted by the graduate lab assistant, in order to demonstrate mastery with this technology. This exam demonstrated our ability to correctly use all of the equipment, and ensured that we could collect accurate data for our study.

Figure 4: fNIRS device worn correctly on the forehead.

2.2 Phase 2- Developing the Mazes

The development of 3D-computer mazes for our project was an important first step in our research. We began this process by reading the MazeSuite manual, and

following the step-by-step directions in order to create a maze in MazeMaker (see figure 5), walk through it in MazeWalker, and view the path, path length, and time used in Maze Analyzer. After we felt comfortable with the steps, we began to create trial mazes by considering the size of the maze, as well as the appearance of the walls, floor, and ceiling, which can all be changed in the program. For our experiment, we needed to have the participant repeat the same maze for several repeated trials. After examining the manual, we learned that this was possible through the list function. Lists allow you to set up the mazes to be performed repeatedly, with messages and rest periods inserted in between them. After experimenting with several maze designs, we met with Dr. Patricia Shewokis from Drexel University, as we were modeling our study after a study she conducted in her lab with Dr. Hasan Ayaz, the creator of MazeSuite. In order to help progress our study, Dr. Ayaz sent us the mazes used in the Drexel study, as well as an orientation maze he created to help participants learn the program functions before beginning the study. However, Dr. Ayaz explained that based upon the results of his study, the mazes may have been too easy to provoke a learning response. After testing these mazes on several volunteers, we also concluded that these mazes were too easy, as participants were able to solve the maze quickly on the first trial. This would not force participants to learn the maze, so we needed to make more difficult mazes to produce a learning response. However, the orientation maze we received from Drexel worked well, so we began to use this with all of our participants. Next, we began to create more complicated mazes by making them larger, and with more turns to reach the exit sign. We decided on a 10x10 maze with

10 turns to reach the end. To examine difficulty, we tested these mazes on several volunteers and created performance curves based on time and path length to examine their difficulty. Based upon the learning curves, we concluded that these mazes were still too easy, as mastery was achieved after only one or two trials. We then moved to 11x10 mazes, still with 10 turns to reach the end. We then tested these mazes with volunteers and examined performance curves. On average, it took participants many trials to solve the mazes, so we determined that these mazes were appropriate. Based upon participant feedback, we decided to add a door at the beginning of the maze, so that participants would know if they were lost and had returned to the beginning of the maze. We also added objects throughout the maze, to help guide participants, but this made the mazes too easy. Thus, after much testing and examining results our final mazes were 11x10, included a door at the start and an exit sign at the end, and required ten turns to reach the exit. We also ensured that there was only one possible correct pathway.

Throughout our preliminary testing of the mazes, we encountered several other problems that we needed to solve. Originally, we planned to have participants complete 50 trials of the maze to study the learning process. However, after having several volunteers attempt this we discovered that it took too long and caused boredom for the participants, which appeared to limit their effort. Because the PFC is involved in working memory, the amount of conscious effort put forth by the participant would affect the results. We also found that some participants were experiencing motion sickness and could not complete all trials of the mazes. To attempt to rectify this

problem, we made the spaces between the walls wider. Additionally, to combat time constrains, boredom, and motion sickness, we reduced the number of trials to be completed from 50 to 10 or 20. With this new protocol, the participant completed 10 trials. If they had not yet mastered the maze, they would complete another 10 trials for a total of 20. This seemed to reduce the problems we were experiencing, but was still enough trials to see a change in path length and path time over the trials. Another problem we experienced was participant frustration. The mazes were set up to run continuously until the participant reached the end point. Some participants were lost in the maze for a very long time. They would get so frustrated that they would give up. This would not allow for accurate data collection, so we added a time limit of two minutes to each maze to combat frustration. This change seemed to combat the motion sickness problem as well. After adding the time limit, we had to make one final change. Originally, we examined path length and time as behavioral measures of learning. With the time limit, any time the maze was not solved, the time would be two minutes, so we could not observe a trend in behavior. Thus, we decided to use path length as the only behavioral measure.

Through our experience with preliminary maze testing, we developed the following final maze protocol. A maze is 11x10 with ten turns, wide walls, and door at the start, and an exit sign at the end. Participants will complete two trials of an orientation maze, followed by ten or twenty trials of the experimental maze, depending on how long it takes for them to reach mastery. Each trial of the

experimental maze has a time limit of two minutes before the next trial begins. The behavioral measure used to examine maze performance is path length.

Figure 5: Example of maze created in MazeSuite, from participants view (not to scale) (13) .

2.3 Phase 3-Testing the Mazes

2.3.1 Participants

Three participants have been examined in this study. Participants in this study are male and female college students, ages 18-22. All participants will be recruited from the student population at the University of Delaware in Newark, DE. Participants will be recruited by word of mouth, and via emails from our professor to her classes.

2.3.2 Data Collection

Participants will come for one testing sessions where they will be asked to traverse a three-dimensional maze presented on a computer screen. Upon arrival, informed consent forms will be administered, and then we will provide instructions about how to complete the task. Upon consent, participants will have their foreheads cleaned using alcohol swabs and the fNIRS sensor pad will be placed on their foreheads. Accurate placement of the sensor pad was ensured by lining up the center-line on the sensor with the center of the nose. Next, the participant will begin a ten second resting period where they will sit with their eyes open looking at the computer screen. This will be used as the baseline condition. Once this is complete, participants are presented with two trials of a simplified orientation maze containing instructions about how the program works. This allows participants to learn the keyboard controls and functions of the maze. Data from the orientation mazes is not analyzed. Following the 2 orientation trials, participants are presented with 10 trials of the experimental maze. Each trial has a time limit of two minutes. If the maze is not completed successfully after two minutes, the trial ends, and the participant is brought back to the beginning for the next trial. If the participant has mastered the maze after 10 trials, demonstrated by successful completion on several successive trials, the equipment will be removed and the participant can leave. If the participant has not yet mastered the maze, he/she will complete and additional 10 trials of the maze, for a total of 20 trials.

2.3.3 Analysis

During each trial and for each participant, we will record time to complete the maze and path length using MazeSuite (MazeSuite, Drexel University, Ayaz H). Using the fNIRS device (fNIR Devices LLC, Potomac, MD) we record the levels of

oxygenated and deoxygenated hemoglobin in the prefrontal cortex (which represent prefrontal cortex activity).

Chapter 3

Results

2.4 Oxygenated Hemoglobin Compared to Trial Number

Figures 6 through 8 examine the brain activation measure of oxygenated hemoglobin. They show the relationship between oxygenated hemoglobin and trial number for each of the three participants. Figure 6, which represents participant one, shows a decrease in oxygenated hemoglobin as trial number increases. The changes are rapid at first, and then slow after many trials have been completed. While not as distinct as for participant one, the results from participant two also display that oxygenated hemoglobin decreased with practice (more trials). While not as clear, figure 7 also displays the typical trend of a performance curve, with HBo levels steadily decreasing and then reaching a plateau. In contrast to participants one and two, the results from participant three do not follow the same pattern. As seen in figure 8, oxygenated hemoglobin increased as trial number increased. This relationship is opposite of that observed in participants one and two, but still has the characteristics of a performance curve. Oxygenated hemoglobin increased rapidly, and then reached a plateau.

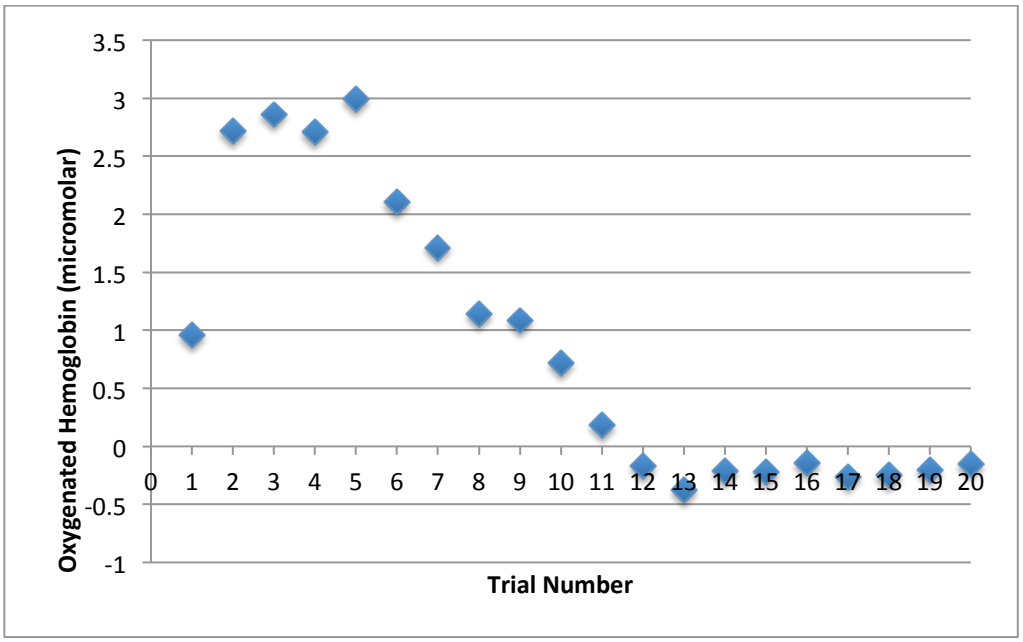

Figure 6: Average change in HBo concentration over 20 trials for participant one.

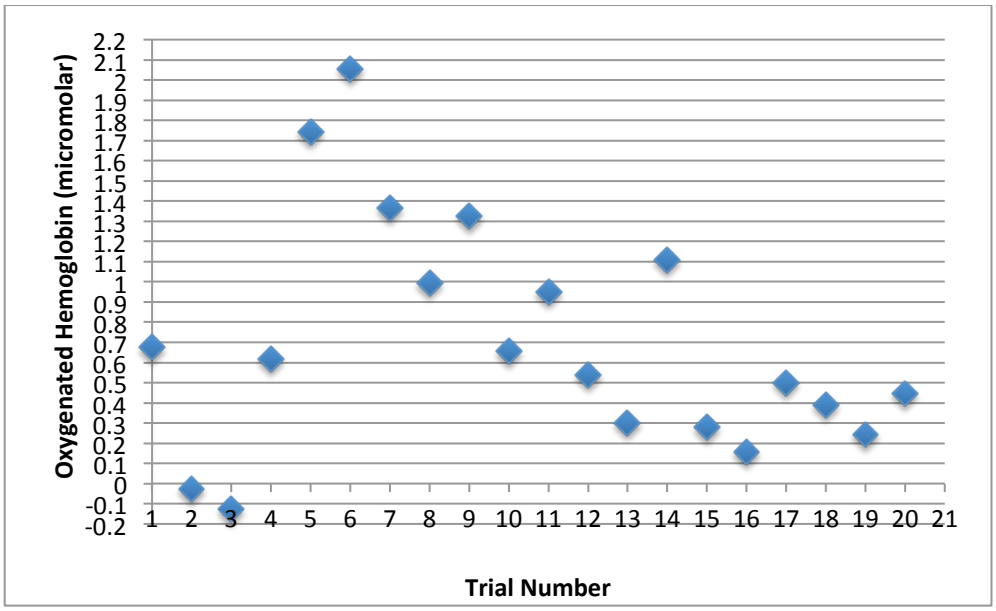

Figure 7: Average change in HBo concentration over 20 trials for participant two.

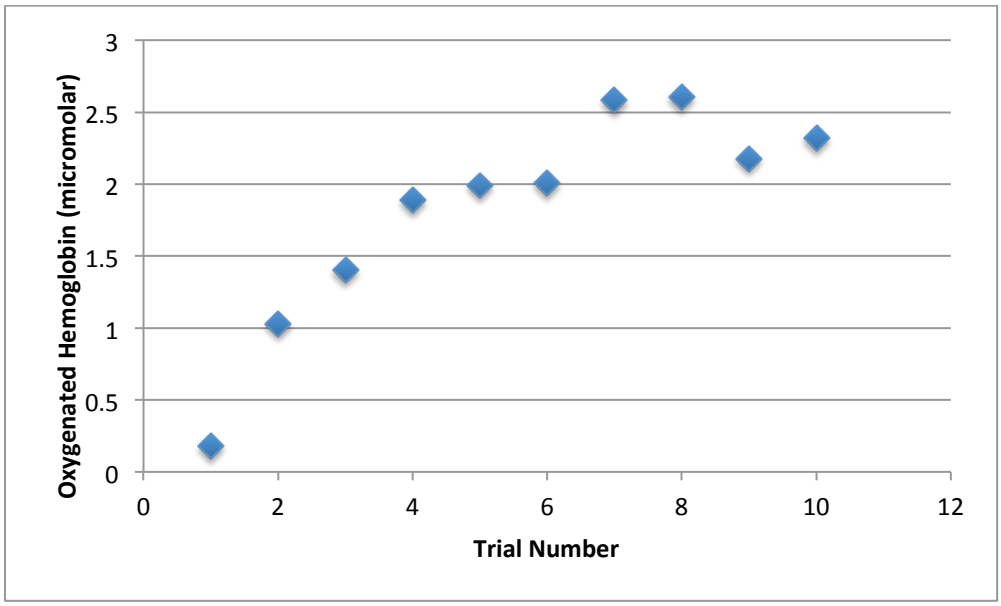

Figure 8: Average change in HBo concentration over 10 trials for participant three.

2.5 Path Length Compared to Trial Number

Figures 9 through 11 examine the behavioral measure of path length. These figures show the relationship between path length and trial number for each of the three participants. Figure 9, which represents participant one, shows a decrease in path length as trial number increases. The changes are rapid at first, and then slow after many trials have been completed. While not as distinct as for participant one, the results from participant two also display that path length decreased with practice (more trials). While less clear, the overall trend in figure 10 also demonstrates a typical performance curve, with HBo levels decreasing and then reaching a plateau. While examining brain activation, the results of participant three did not follow the pattern; this was not the case when examining path length. As seen in figure 11, path length increased as trial number increased, akin to participants one and two. The characteristics of a performance curve are again observed in figure 11. Path length

decreased rapidly, and then reached a plateau. For participant three, path length reached a plateau much faster than it did for participant one or two. For all three participants, the shortest path length reached was approximately 50 maze units.

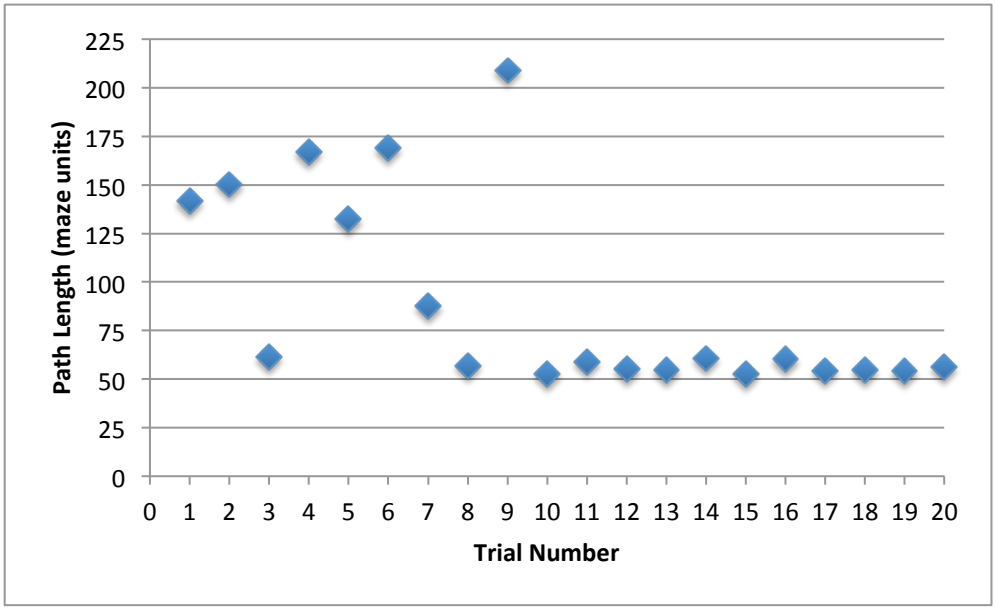

Figure 9: Change in path length over 20 trials for participant one.

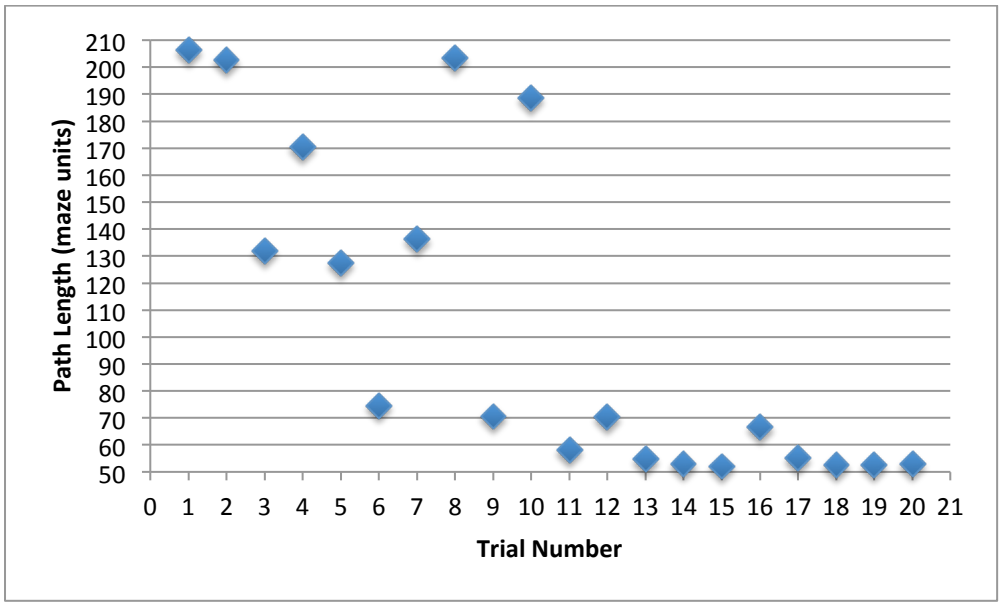

Figure 10: Change in path length over 20 trials for participant two.

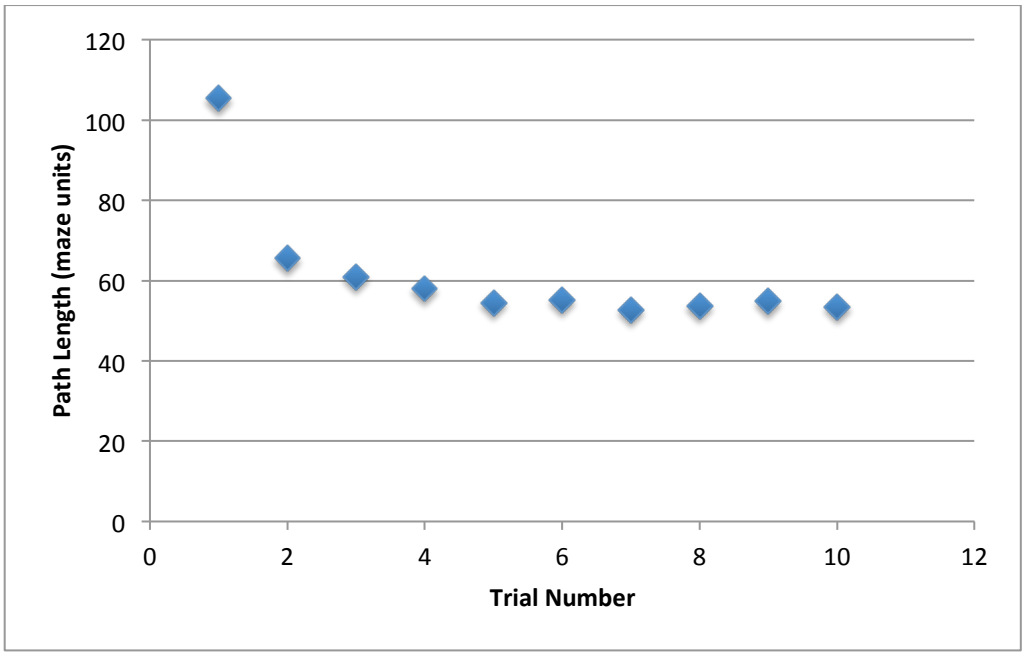

Figure 11: Change in path length over 10 trials for participant three.

2.6 Oxygenated Hemoglobin Compared to Path Length

Figures 12 through 14 compare the relationship between the brain and behavioral measures. These figures show the relationship between HBo and path length for each of the three participants. As seen in figure 12, the results from participant one show a direct linear relationship between oxygenated hemoglobin and path length. As path length decreased, HBo decreased. The R-value for this data is 0.64. The data from participant two, in figure 13, demonstrate no correlation between HBo and path length. The R-value for this data is 0.008. The data in figure 14, representing participant three, show an indirect linear relationship between HBo and path length. As path length decreased, HBo increased. The R-value for this data was 0.89.

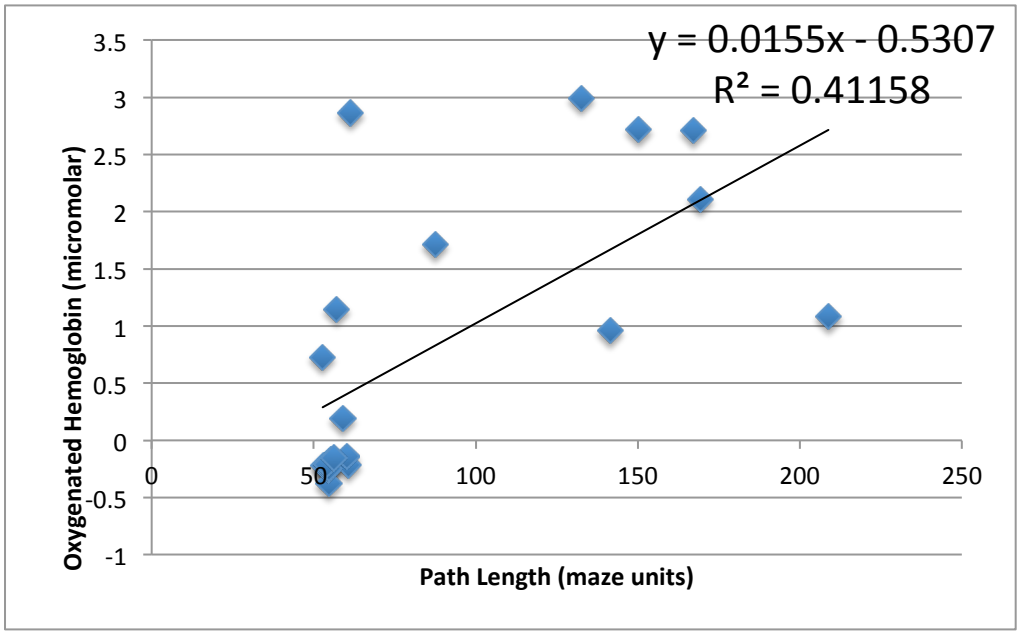

Figure 12: Average HBo concentration compared to path length over 20 trials for participant one.

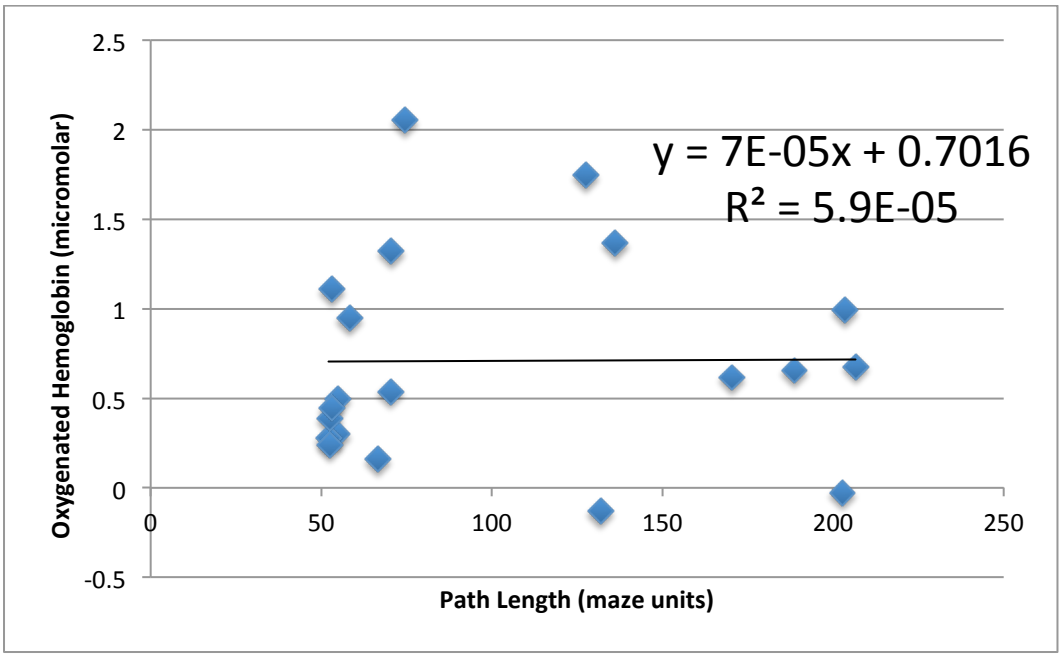

Figure 13: Average HBo concentration compared to path length over 20 trials for participant two.

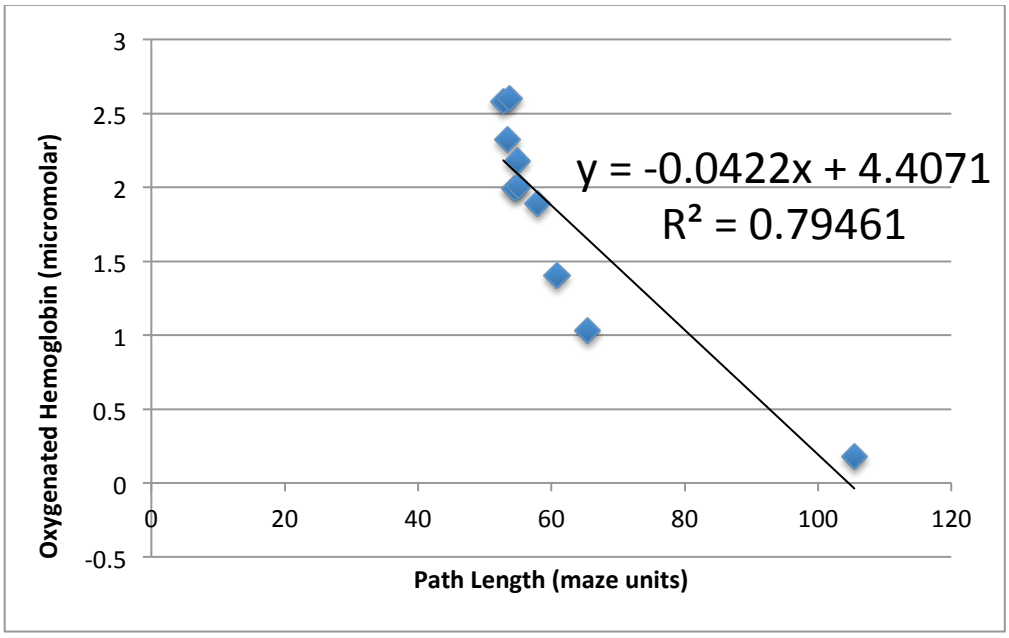

Figure 14: Average HBo concentration compared to path length over 10 trials for participant three.

Chapter 3

Discussion

3.1 Analysis of Data

Examining path length over the trials, the data support our hypothesis that with practice, path length would decrease. This trend is visible in the data for all three participants as seen in figures nine through eleven. The decrease in path length represents more efficient maze completion. Very high path lengths occur when the participant could not solve the maze, or were lost many times before finding the exit. The path length decreases, as the participant does not make as many wrong turns, and finds the exit each time. Finally, the path length is at its minimum and plateaus when the participant makes no wrong turns and has thus found the shortest path to the exit. As participants are able to make less wrong turns, they are learning the correct path to take. When their path length plateaus, they have successfully learned the maze and reached mastery.

While participants one and two reached their lowest path length slowly, participant three reached the lowest path length, and thus learned the maze, after only one trial. This can be seen in figure 11, where the plateau begins at trial two. Despite these differences, all three participants plateaued at a path length of approximately 50 maze units. This implies that they all were able to find the one ideal path to reach the exit. All three participants learned the maze successfully, they just reached maximum performance at different speeds.

The results shown for participants one and two support our hypothesis that with practice (more trials), oxygenated hemoglobin would decrease. In figure 6, the

trend is very clear as oxygenated hemoglobin starts at high levels, rapidly decreases, and then reaches a plateau when the maze was mastered. In figure seven, while not as clear, a downward trend in HBo is still observed. This hemodynamic change observed quantifies brain activity. With brain activation, blood flow to the activated brain areas increases, to supply the brain with the nutrients it needs to function. Blood flowing into the brain has a high concentration of oxygenated hemoglobin, so this increases as well. Thus, the changes in HBo observed during the maze trials indicate changes in brain activity. Thus, as HBo was high in the early trials, PFC activity was also increased. As the trials went on and HBo decreased, PFC decreased as well. This supports the theory that in later learning, the higher-order functions of the PFC are not needed and the PFC drops out, allowing the subcortical pathways to take control of the skill execution (11) .

While the results for participants one and two support this hypothesis, the results from participant three do not. HBo increased as more trials were completed. This implies that PFC activity increased rather than decreased over the 10 trials completed by participant three. This is not the expected response, but a possible explanation might be the speed with which participant three mastered the mazes. Looking at figures 9 and 10 as a comparison, it is observed that participants one and two did not master the maze until around trials 10 and 13 respectively. However, figure 11 shows that participant three mastered the maze at trial two. This early mastery of the maze may have contributed to the unexpected HBo results for participant three. He was not learning the maze throughout the 10 trials, as it was already mastered. It is possible that the increase in activity in his PFC was due to focus

on unrelated tasks or thoughts, since this participant did not have to actively think about the maze.

Figures 12 through 14 compare the behavioral measure of path length to the brain activation measure of HBo. For participant one, the results support our hypothesis that there would be a direct linear relationship between HBo and path length, as path length decreased, HBo decreased. The R-value for this data was 0.64, indicating a true positive correlation between the two variables. For participant two, the results did not support our hypothesis. The R-value for this data was 0.007, which indicates that there was no correlation between path length and HBo. This may have occurred because the results from participant two, for both path length and HBo, were inconsistent. While both followed a general trend of decreasing over the 20 trials, there were many outliers in both data sets, as seen in figures 7 (HBo) and 10 (path length). Further investigation of the cause behind this outcome is necessary. The results for participant three also do not support our hypothesis. While we hypothesized that HBo would decrease as path length decreased, figure 14 shows an increase in HbO as path length decreased. As previously explained, this may be due to the participant's quick mastery of the task as compared to the other two participants. The R-value for participant three's data was 0.89. This indicates a strong correlation between the two variables.

3.2 Changes in the Study

The original aim of this study was to use fNIRS and MazeSuite to analyze brain and behavior patterns, during skill learning, in children with Developmental Coordination Disorder (DCD), and compare this to patterns observed in typically developing children. Six to thirteen percent of school-aged children suffer from

Developmental Coordination Disorder (DCD). Children with DCD are classified as having motor delays complex enough to interfere with their academic progress and activities of daily living (20) . Because of their motor coordination challenges, children with DCD often have difficulty performing every day tasks such as brushing their teeth or zippering a zipper (21) . The difficulties they face put them at later risk for long-term poor academic achievement, difficulties interacting with peers, and long-term health problems due to their ensuing inability to participate in physical activity (22) . Substantial evidence exists that children with DCD have more variable motor performance when compared to typically developing (TD) children who perform the same task (20, 23) . Although we know that children with DCD are more variable on motor performance tasks, no research to date has investigated the underlying neurological cause behind this. We hoped that our study would allow us to begin to examine the cause behind skill performance variability in children with DCD, as it may be linked to differences in the PFC. However, due to complications with the fNIRS technology and MazeSuite program, we instead focused on the learning process as a whole, as a preliminary study, to pave the way for a future study on children with DCD. The aim of the current study focused on using MazeSuite to develop mazes that are within a correct difficulty level to portray an expected learning curve. Additionally we compared brain and behavioral measures during 3D-maze completion in order to test the hypothesis that brain activation patterns match behavior patterns. This comparison is a foundation that will be used in future studies in the Developmental Motor Control Laboratory (Dr. Nancy Getchell).

3.3 Future Directions

This experiment allowed us to determine the relationship between brain (HBo) and behavioral (path length) measures during a 3D-computer maze task. We found that in general, HBo decreases as path length decreases, indicating a decrease in activation of the prefrontal cortex as learning progresses. Several steps can be taken to further this experiment. First, using more advanced statistics could lead to a better understanding of the data. We only examined the R-value, which allowed us to see if there was a significant correlation between HBo and path length. However, this may not have been accurate due to the small sample size of participants. Re-examining the correlation after testing more participants could allow for more accurate interpretation of the results. Additionally, using an R-value assumes that the correlation between HBo and path length is linear. For participants one and two this seemed to apply, however for participant three, the curve almost seems quadratic in nature. Finally, using more advanced statistical analysis, more than a simple R-value, may lead to stronger conclusions.

Another future step should be to examine different regions of the prefrontal cortex separately. To examine prefrontal cortex activity, we looked at average activity across the sixteen channels throughout the whole trial. Examining just the channels that look at the left or right PFC, or medial vs. lateral PFC, may provide the most accurate picture of prefrontal cortex activity. While as a whole, the PFC is responsible for executive functions such as planning and decisions making, specific functions occur in different regions. The dorsolateral region of the PFC is responsible for spatial working memory tasks, but the ventolateral region controls working memory tasks that involve manipulating specific objects (9). For this study, examining the dorsolateral PFC activity may provide more conclusive results as the maze is a spatial

task. Looking at different regions of the PFC may also help determine whether the participant is focusing on the maze, or external information. As mentioned previously, it is possible that in our study, participant three was focused on something besides the maze, which is why HBo increased rather than decreased. This could be further investigated by examining specific regions. Another step that could be taken to allow for more accurate interpretation of the fNIRS data is to look at the differences in HBo over one block. We averaged the values for each block, but you could instead look at the HBo values for each second of the trial, to get a more accurate picture of the hemodynamic response. Finally, while we only considered HBo values when analyzing the data, it would be interesting to also examine the HBr data in the future. We only examined HBo due to time constraints, and because it has been shown that HBo is a more accurate indicator for changes in cerebral blood flow (15) . However, in the future it would be important to determine if the HBr concentration also follows the predicted pattern of decreasing as learning progresses.

During our study, we used manual event markers, rather than automatic event markers, when marking the trials in COBI studio. In the future, it will be important to set up automatic event markers, as using manual markers creates a source of error. It is difficult to manually press the marker exactly when the mazes begin and end. Human reaction time alone causes error when placing the event markers. Automatic markers would eliminate the need for a person to press the marker, also eliminating this source of error from the data. This would create blocks of data that are more consistent with the actual length of the trial.

The previously mentioned suggestions are ways that this study could be improved, or that further conclusions could be drawn from the data collected.

However, in the future, this experimental protocol could also be used for further research. fNIRS and MazeSuite could be used to examine the contextual interference (CI) effect in adults and typically developing children. The CI effect is a principle of learning which states that higher CI (random practice) during acquisition of a skill leads to increased learning (24) Using fNIRS to examine the CI effect in adults could provide physiological evidence for the CI affect, which has been consistently observed in human behavior, but does not have evidence of brain activity to support it. A comparison of PFC activity in children and adults, while studying the CI effect, could give insight into developmental differences in mature and immature brains. This could be expanded to study children with disabilities. Comparing the maze results and PFC activity of typically developing children and children with disabilities may provide insight into how the disability affects brain function. If it were found that PFC activity differs in children with disabilities, this would be an area for further research that would hopefully lead to an intervention targeting skills such as planning and decision-making, controlled by the PFC.

REFERENCES

1. Schmidt R, Lee T. Chapter 8: Introduction to motor learning. In: Motor Learning and Peformance: From Prinicples to Application. 5th ed. Champaign, IL: Human Kinetics; 2014. p. 175-195.

2. Schmidt R, Lee T. Chapter 9: Skill acquisition, retention, and transfer. In: Motor Learning and Performance: From Principles to Application. 5th ed. Champaign, IL: Human Kinetics; 2014. p. 197-226.

3. Tom malaher's brain scan [homepage on the Internet]. [cited May 27, 2015]. Available from: http://malaher.org/2007/03/pet-peeve-learning-curve-misuse/.

4. Huey ED, Krueger F, Grafman J. Representations in the human prefrontal cortex. *Current Directions in Psychological Science.* 2006; 15(4): 167-171.

5. Miller EK, Freedman DJ, Wallis JD. The prefrontal cortex: Categories, concepts, and cognition. *Philosophical Transactions of The Royal Society B: Biological Sciences.* 2002; 357(1424): 1123-1136.

6. Alvarez JA, Emory E. Executive function and the frontal lobes: A meta-analytic review. *Neuropsychology Review.* 2006; 16(1): 17-42.

7. Getchell N. Basic neuroanatomy of motor control. 2015.

8. Leff D, Orihuela-Espina F, Elwell C, Athanasiou T, Delpy D, Darzi A, Yang G. Assessment of the cerebral cortex during motor taks behaviors in adults: A systematic review of functional near infrared spectroscopy (fNIRS) studies. *NeuroImage.* 2011; 54: 2922-2936.

9. Paik E. Functions of the prefrontal cortex in the human brain. *Journal of Korean Medical Science.* 1198; 13: 569-581.

10. Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience.* 2001; 24: 167-202.

11. Getchell N. Putting it all together. 2015.

12. Gentilli R, Shewokis P, Ayaz H, Contreras-Vidal J. **Functional near-infrared spectroscopy-based correlates of prefrontal cortical dynamics during a cognitive-motor executive adaptation task**. *Fronteirs in Human Neuroscience.* 2013; 7: 277.

13. Ayaz H, Shewokis P, Curtin A, Izzetoglu M, Izzetogulu K, Onaral B. **Using MazeSuite and functional near infrared spectroscopy to study learning in spatial navigation**. *Journal of Visualized Experiments.* 2011(56).

14. Villringer A, Planck J, Hock C, Schleinkofer L, Dirnagl U. **Near infrared spectroscopy (NIRS): A new tool to study hemodynamic changes during activation of brain function in human adults**. *Neuroscience Letters.* 1993; 154(1-2): 101-104.

15. Ehlis A, Bahne C, Jacob C, Herrmann M, Fallgatter A. Reduced lateral prefrontal activation in adult patients with attention-deficit/hyperactivity disorder (ADHD) during a working memory task: A functional near-infrared spectroscopy (fNIRS) study. *Journal Of Psychiatric Research.* 2008; 42: 1060-1067.

16. Blasi A, Elwell CE, Lloyd-Fox S. Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy. *Neurosci Biobehav Rev.* 2010 02; 2015/5; 34: 269+.

17. Strangman G, Boas D, Sutton J. Non-invasive neuroimaing using near-infrared light. *Biological Psychiatry.* 2002; 52(7): 679-693.

18. Van Horn J, Gold J, Esposito G, Ostrem J, Mattay V, Weinberger D, Berman K. Changing patterns of brain activiation during maze learning. *Brain Research.* 1998; 793: 29-38.

19. Ayaz H, Allen S, Plateck S, Onaral B. Maze suite 1.0: A complete set of tools to prepapre, present, and analyze navigational and spatial cognitive neuroscience experiemnts. *Behavior Research Methods.* 2008; 40(1): 353-359.

20. Whittal J, Getchell N, McMenamin S, Horn C, Wilms-FLoet A, Clarke J. Perception-action coupling in children with and without DCD: Frequency locking between task-relevant auditory signals and motor responses in a dual-motor task. *Child: Care, Health & Development.* 2006; 32(6): 679-692.

21. Overview of DCD [homepage on the Internet]. McMaster University: Centre for Childhood Disability Research. 2014 [cited 9/24/14]. Available from: http://dcd.canchild.ca/en/AboutDCD/overview.asp.

22. Gillberg C, Kadesjo B. Why bother about clumsiness? the implications of having developmental coordination disorder (DCD). *Neural Plasticity.* 2003; 10(1-2): 59-68.

23. Hulme C, Biggerstaff A, Moran G, McKinlay I. Visual, kinesthetic, and cross-modal judgements of length by normal and clumsy children. *Developmental Medicine and Child Neurology.* 1982; 24: 461-471.

24. Feghhi I, Abdoli B, Valizadeh R. Compare contextual interference and practice specificity in learning basketball free throw. *Procedia- Social and Behavioral Sciences.* 2011; 15: 2176-2180.