EXECUTIVE FUNCTION AT DIFFERENT LEVELS OF TASK DIFFICULTY

by

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ABSTRACT

The objective of this study was to demonstrate that executive function increases when one is completing a difficult task that requires motor planning. The study aimed to demonstrate that functional near infrared spectroscopy is a valid tool for measuring prefrontal cortex activation. The Tower of Hanoi was used as a problem-solving task that elicits executive function. The problem-solving task could be manipulated to be operationally defined as easy or difficult. The study did not show a statistically significant increase in executive function with a more difficult task in a statistically significant manner ($p>0.05$). However, ancillary analysis reveals that in certain cases where the experimental design worked effectively results showed prefrontal cortex activation was indeed increased. When experimental design was flawed and did not accurately test what was intended, results were confounded. Ultimately, descriptive statistics do not accurately depict what was occurring in the study and further investigation is necessary.

Chapter 1

INTRODUCTION

1.1 Executive Function (EF)

Executive function (EF) is a collective set of cognitive processes that allow one to make conscious decisions and exhibit awareness. Examples of EF include the ability to discern correct from incorrect, plan or organize, and alter focus or attention. EF is a top-down processing system that requires cortical activation of the brain. This study aims to better understand EF by tracking cortical activity while one is completing executive tasks of varying difficulty.

There are three components that make up executive function. These components include inhibitory control (IC), working memory (WM), and cognitive flexibility (CF). IC is the ability to resist impulses or manage intrinsic urges elicited by external stimuli (5). A classic example of IC is the ability of a trained dog to remain sitting while a ball is thrown. Dogs that lack IC would simply begin chasing the ball as soon as it is thrown. This IC is imperative in everyday life activities such as driving and is even involved in emotional behavior such as the ability to withhold violent urges when one is angry. Ultimately, IC is responsible for one's self-discipline (5).

WM is the ability to take information that one just received and integrate it into the selection of the proper response. A common example of WM is the ability to remember a question on a test while selecting an answer to it. Without WM one would simply be stuck rereading the question without ever having the chance of selecting an

answer because they could never retain what the question was asking and integrate it with the possible answers. WM is different from short-term memory because it involves the integration of the new memory whereas short-term memory only involves the storage of the information (5).

CF is a more complex component but can fundamentally be described as the ability to see things both spatially and figuratively from different perspectives. An example of the figurative style of perspective is the ability to consider another's opinion or point of view. Spatially, CF is very active when solving a puzzle similar to a Rubik's cube. One must be able to mentally envision what will happen if they turn the cube a certain way. IC, WM, and CF all constitute major roles normal in brain function (5).

When there are issues with EF and one does not possess traits like inhibitory control, WM, or cognitive flexibility normal life becomes extremely difficult and those who lack these cognitive abilities are debilitated. One of the most important diseases that involve lack of EF is Developmental Coordination Disorder (DCD). According to the American Psychiatric Association DCD is prevalent in about 5-6% of school aged children and is characterized by severe motor impairment but its mechanism is not very well understood (1).

In order to better understand DCD this study investigates prefrontal cortex activation while one is performing a motor task that requires EF. Studies have suggested that the prefrontal cortex of the brain is the location where much of EF is carried out and because of this the prefrontal cortex is a primary area of interest when investigating EF (10).

1.2 The Prefrontal Cortex (PFC) as it Relates to Executive Function

The prefrontal cortex (PFC) is the anterior portion of the frontal lobe of the human brain. The PFC is believed to be involved in executive function (10) and known to be the center of motor planning during response selection. It is the part of the brain that integrates sensory information and then selects a motor response (10). The PFC is the ideal area of interest for a brain imaging study that requires subjects to interpret sensory information, strategically plan, and subsequently execute motor tasks.

Due to the anatomical location of the PFC it is a very popular focus of study for neurological imaging technology. As a result of growing technology and the PFC's neuroanatomical availability the Developmental Motor Control lab at the University of Delaware obtained the noninvasive neuroimaging device fNIRS. FNIRS is an acronym for functional near infrared spectroscopy and is explained in an upcoming section.

One of the strongest pieces of empirical evidence supporting the role of the PFC in higher-level cortical processes of EF is seen when there is damage to the PFC. It was demonstrated that individuals who had damage to their PFC suffered detrimental deficits in attentional focus and inhibitory control (3). This evidence very strongly suggests that the PFC is involved in the conscious processes of EF. Another study examined the size of the PFC in animals and compared that to the size of the human PFC, revealing that humans have much larger PFCs (10). One cannot assume that because humans have a relatively large PFC, the PFC is responsible for conscious awareness and thought processes. Additionally, based on that evidence alone, one cannot claim that the PFC is the reason humans are cognitively advanced. However,

when the size is coupled with the demonstration of how injury to the PFC elicits attentional deficits the evidence begins to suggest that the PFC is indeed responsible or at least contributes to these capabilities.

One of the most important aspects of the PFC is its role in inhibition of "bottom up" impulses and its implementation of "top-down" processing. Bottom up impulses are best described as intrinsic reactions such as the ability to immediately move if you see an object about to hit you. Such bottom up processes are necessary in instances that require instinctual reaction. But, there are many cases where one must inhibit their bottom-up impulses with IC. When a bottom up reaction is inhibited it is then considered top-down processing and is vital to humans unique cognitive ability. Again, it has been demonstrated that those who have damage to the PFC exhibit a lack of top-down processing and do not have inhibitory control (3).

1.3 Tower of Hanoi (ToH)

A valid and reliable tool used to examine executive function in children and adults is the Tower of Hanoi (ToH). ToH is a problem-solving task that has been standardized for neurological imaging (12). Previous studies have used neurological imaging like positron emission tomography (PET) or fNIRS to detail neural circulation during problem solving (12). Even when rules or settings of ToH are changed, studies have demonstrated that the PFC is always active during this problem-solving task. More specifically, the anterior, dorsolateral, and inferior aspects were shown to be continually active (4).

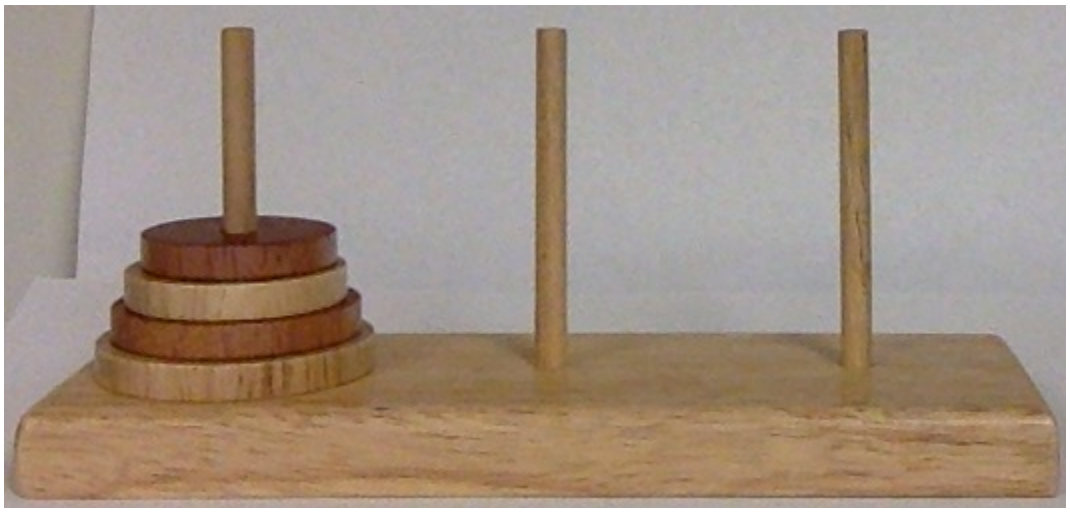

Figure 1. A manual version of the Tower of Hanoi (ToH).

Figure 1 depicts a manual edition of the ToH. ToH tasks involve moving the disks from a starting position to a specified ending position in the minimum amount of moves. This requires strategic planning because the rules state that only one disk can be moved at a time and a larger disk cannot be placed on top of a smaller disk. The puzzles can become more complex as more disks are added or by adjusting the starting position to require more moves. Both methods of increasing the complexity add difficulty by increasing the minimum amount of moves. Increasing the minimum amount of moves requires more planning in order to accomplish the task.

There are also variants of the ToH that are used in other studies such as the The Tower of London (ToL) (13) or the Scarborough adaptation of The Tower of London (S-ToL) (12). These variants differ by setting other parameters such as only allowing one disk to be placed on the furthest left peg, whereas the ToH has no restrictions as to how many disks can go on a peg. The ToH is a useful standard for a problem-solving

task because it correlates well to other tasks, like the ToL or the S-ToL, that involve tactful planning and information processing in spatial working memory (4). The correlation between ToH and many other tasks that involve such planning widens the scope of the study. The results can be generalized to a wide variety of activities making the ToH an ideal task for this study.

1.4 Functional Near Infrared Spectroscopy (fNIRS)

Functional Near Infrared Spectroscopy or (fNIRS) is an indirect optical imaging device that is used to measure local blood oxygenation levels. fNIRS has been shown to be a reliable method for calculating oxygenation of many different parts of the body (11). fNIRS functions by emitting different wavelengths of infrared light (700-1000 nm) and then interpreting the response of the light that is reflected back to its sensor pads (15). Since oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HbR) absorb different wavelengths of light the fNIRS sensor pad can interpret what type of tissue, HbO_2 or HbR, is inside the body at the site being tested. HbO_2 and HbR are the two main chromophores, or molecules that absorb light, at the 700-1000 nm range ensuring that the changes seen when using fNIRS are due to relative concentration changes of HbO_2 or HbR (9). If there are high levels of HbO_2 it indicates that there is no oxygen use locally at that area. Conversely, if there are high levels of HbR it means the oxygen at that location has been used. Ultimately, fNIRS uses laws of hemodynamics to interpret the relative concentrations of HbO_2 or HbR but the basis of the measurement comes from what type of tissue is being tested (11).

Near-Infrared light has the capability to penetrate soft tissue as well as bone, which makes it an ideal instrument for imaging the intact skull (8). What separates fNIRS, making it one of the best contemporary methods of brain imaging. It is non-invasive which is an extremely important factor in brain imaging. Other indirect brain imaging techniques such as a PET scan require the introduction of radioactive isotopes into the blood to examine hemodynamics of the isotopes once they reach the brain (14). Also, fNIRS uses wavelengths just longer than those of visible light ensuring that no tissue damage occurs due to radiation.

One of the largest benefits of using fNIRS is its accuracy even when there is motor artifact. This separates fNIRS from many other indirect imaging devices because most of them require little to no movement while in operation. fNIRS ability to be accurate by removing motor artifact makes it ideal for studying tasks that require everyday motor movement. Finally, the last benefit of fNIRS is its portability (9). The goal of this study is demonstrate that PFC activation is increased when a person is actively planning strategically. This will hopefully lead to future investigations on how more difficult tasks influence patients with DCD.

Chapter 2

METHODOLOGY

2.1 Protocol

The experimental protocol was designed to ensure that the proper data was collected in an unbiased and accurate manner. Ten University of Delaware students were tested during this study (five females and five males). The age range was 18-22 years old (21.5 (+/-) 1.5 years). The first step of the protocol required that all subjects completed and provided the Institutional Review Board (IRB) informed consent. The informed consent was accompanied by a verbal explanation of the purpose of the study and assuring that the subject was aware they could cease their role in the experiment at any point in the study. The informed consents were signed by both the subject and experimenter and filed immediately in a locked drawer. Next the subjects were asked to fill out a demographic data sheet with a subject code label in order to ensure any information provided by the subject was confidential and experimenters exclusively referred to the subject by their code number. The demographic data sheet with the subject's identity was also immediately filed, stored, and locked in a drawer separate of the IRB consent forms. Lastly, subjects were asked to fill out an Edinborough Handedness Survey. The handedness survey was not relevant for this study but was necessary for a colleague's experiment.

In order to ensure intersubject consistency PowerPoint slides were designed for both the computerized version of the ToH and the manual version of the ToH for each puzzle set. The manual edition slides displayed the solution for each puzzle, which is presented on the screen for the participant to view. The slides then change to a break period and then the next puzzle will be shown. The computerized edition is designed to display the starting position for the participant and then the participant can interactively solve the puzzle on screen.

After all the appropriate paperwork was filled out and filed, subjects could then begin the next part of the experiment. In order to ensure that all subjects were proficient at the ToL they were required to complete five practice puzzles in the manual version of ToL and then the same five puzzles on the computerized edition. The five puzzles were designated specifically for practice and were not used at any other part in the experiment. All puzzles were selected from a previously designed list of 22 puzzles from a prior study that utilized the ToH (16). All puzzles used four disks and three pegs, but utilized a variety of different starting and ending positions.

The practice phase of the study consisted of five puzzles that were completed in both the manual version and the computerized version. In the manual edition, subjects were given the wooden set with the puzzles in the appropriate starting position and were shown the solution on a separate picture. In the computerized edition subjects sat on the same chair they would be sitting in the experiment and completed the puzzles on the same software used during the experiment. Subjects were shown the solution on a separate piece of paper for the computerized edition as

well. Once the subjects completed the five puzzles on both the computerized and manual editions they were asked if they were comfortable and willing to take the proficiency test. The 5 practice puzzles varied in difficulty and were puzzle numbers (1,8,15,16,22).

After subjects completed the practice phase they were asked if they were comfortable with the game and would be willing to take a proficiency test. The proficiency test was implemented to demonstrate that the subjects understood the game and the strategy while also minimizing any effects of a learning curve during data collection. The proficiency test consisted of three puzzles, different from the five used in practice and the ten used in data collection. In order to be deemed "proficient" subjects had to finish each puzzle within 60 seconds and could execute no more than five moves over the minimum amount moves required by that puzzle.

After successful completion of the proficiency test, subjects moved on to the ten puzzles for data collection. The ten puzzles were used to create two sets of puzzles; each consisting of the ten puzzles but in different orders. The ten puzzles were selected to ensure a variety of difficulty and the order was randomized in order to prevent the subjects from "block" learning or memorizing the order of the puzzle. Subjects were required to wear the fNIRS headband for both puzzle sets. Also, both the set number, (set one or set two), and puzzle type, (manual or computerized), were varied in order to remove any effects of a learning curve. The subjects completed their participation in the study once they completed both sets one and two.

Once the data were obtained via the COBI studio technology they were then saved in a file folder on the computer under that subject's code. The COBI studio technology gives the capability for editing and selecting the data recorded from the fNIRS device. Later, the data were processed and analyzed in an excel spreadsheet. The experimental protocol was completed once all data were processed.

2.2 Data Collection

2.2.1 Inclusion Criteria

The proficiency test consisted of three puzzles of varying difficulty. The experimenters operationally defined inclusion criteria for a "proficient subject" as completion of the puzzle within 60 seconds and only using five moves or less over the minimum amount of moves for that puzzle. Having puzzles of various difficulty assured that subjects were exposed to all the types of puzzles they would see in the actual experiment. Also, by utilizing this standard ensured that subjects were all equally knowledgeable of the game and the best tactics for successful completion. Making all subjects similar eliminated learning effects that would have been prevalent if one subject was previously exposed to the ToH and the other was not.

The proficiency test was only completed on the computer and used the same software that was used in data collection. Also, subjects were in the same seat that they would be in during the data collection. The proficiency test was intended to be similar to the experimental procedure in order to make the subject comfortable and

have the process feel routine in order to minimize any surprises during testing. The only differences between the proficiency test and the experimental testing were the fNIRS device was not worn during the proficiency test and the proficiency test was exclusively on the computer with the lights on.

2.2.2 Puzzle Sets One and Two

Once subjects successfully completed the practice phase and the proficiency test they were able to begin completing puzzle sets one and two. This stage was when data were collected, so the fNIRS headband was worn and the lights were turned off. Turning off the lights reduces the affects of ambient light and ensures all light received by the fNIRS sensor pad is the infrared light emitted form the sensor itself. The COBI studio software was opened once the headband was in a comfortable position and the lights were turned off. Any necessary adjustments were made to the software in order to assure that all optodes were reading in the correct range (400-4000 Hz). Subjects were asked to minimize any unnecessary motor movement in order to minimize unwarranted movement artifact in the data. Once all the correct preparations were made the subjects were able to begin solving puzzles.

The orders of set (one or two) and puzzle type (manual or computerized) were randomized in order to minimize learning effects. Subjects were given a 30-second break between each puzzle. During the manual testing, subjects were given the preset starting position, the computer controlled timing, and the screen displayed the

solution. This process was repeated for all ten puzzles of that set and a short break followed while the experimenters prepared to the next version of the puzzles.

Alternatively, the subject could have the computerized version first. During the computerized version the subjects were given the starting position on the computer screen with the solution shown on a picture immediately to the right of the screen. Subjects clicked and moved puzzle pieces until the puzzle was solved. Again, the subjects received a 30 second break between puzzles. This process was repeated for all ten puzzles and then the subject continued on to the wooden version. Both the computerized and the wooden trials were recorded for every participant and the number of moves was retroactively recorded in order to ensure no mistakes were made while trying to do it in real time.

The operator of the COBI studio made a marker by pressing "1" as soon as the subject was to begin their first puzzle set but before any puzzles were actually solved. The "1" marker was also made when the subject completed there first puzzle set along with the beginning of puzzle set two and the end of puzzle set 2. These markers give an indication of the temporal location of puzzle solving process with respect to the fNIRS data, useful later in data processing and analysis. The fNIRS operator always pressed "3" once the subject was initially exposed to a puzzle. The "3" then always signifies that the subject has just seen the puzzle. Then, the operator presses the "4" marker once the subject begins their first move. Lastly, the fNIRS operator pressed the "5" marker once the subject completed the puzzle.

Making these markers gives blocks of different phases in the puzzle solving process that can be stratified and used in data analysis. Block "3-4" is a time strictly consisting of strategic planning with all motor movement absent. Block "4-5" is a time of both strategic planning accompanied with motor movement. Finally block "5-3" is a time of rest.

Puzzle sets one and two consisted of the same ten puzzles but were preset in different orders. The puzzles varied in difficulty in order for equal distribution of puzzle types. The same ten puzzles were used in both the computerized and manual versions in order to ensure equal difficulty for the different modes of the game. The comparisons for computerized vs. manual editions were not the aims of this experiment.

Table 1:Minimum number of moves for the five easiest puzzles and the five hardest puzzles.

# Minimum Moves Easy Puzzles	# Minimum Moves Hard Puzzles
8	12
8	13
11	13
11	15
12	15

2.3 Data Processing

After data were collected, the de-identified data were stored in a file folder on a computer in the Developmental and Motor Control Lab with that subject's code. The

data was then opened in the fNIRSoft technology and was processed. Data processing involves analyzing the markers and refining the data. The HbO, HbR, and total oxygenation data were exported to excel files. Once in the excel file average oxygenation was calculated individually for each of the 16 optodes, collectively for all 16 optodes, and the time per puzzle was calculated from this information. Lastly, moves were counted and recorded for each puzzle. T-tests were used to determine if moves were statistically higher for the more difficult puzzles, if time was significantly longer for the difficult puzzles, and if PFC oxygenation concentration was higher for the more difficult puzzles. All t-tests values were calculated via Microsoft Excel.

Chapter 3

RESULTS

3.1 Puzzle Difficulty Comparing Number of Moves Made

Table 2 and Figure 2 demonstrate descriptive statistics of the number of moves made by all subjects. As seen in Table 2 the average number of moves for the difficult puzzles is higher than the average number of moves for the easier puzzles. Also, when compared in a paired t-test the average number of moves is significantly higher ($p<0.05$) in the five more difficult puzzles than it was in the five easier puzzles ($p=3.32*10^{-6}$). Figure 2 pictorially demonstrates the difference in the number of moves used in the easiest five puzzles and the hardest five puzzles. All descriptive statistics values were calculated using additive values both manual and a computerized edition for the easiest five puzzles collectively and then the hardest five puzzles collectively.

Table 2: Descriptive Statistics of the Number of Moves in the Five Easiest Puzzles and the Five Hardest Puzzles

Average Moves Easy	**Average Moves Difficult**
14.65 +/- 7.42	19.12 +/- 6.78
Total Moves Easy	**Total Moves Difficult**
1465	1912

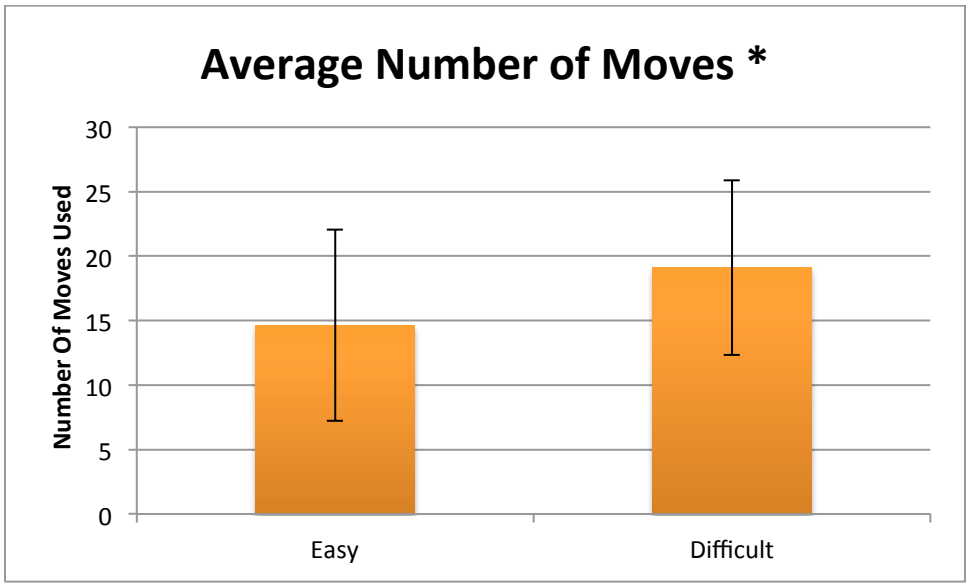

Figure 2: The average number of moves in the five easiest puzzles compared to the five hardest puzzles. * Indicates that $p<0.05$. $P=0.001$

3.2 Puzzle Difficulty Comparing Time Taken to Solve

Table 3 and figure 3 represent the descriptive statistics for the time taken to solve the easiest five puzzles and the hardest five puzzles. The mean, standard deviation, and total time account for the easiest five puzzles total time and then the five hardest puzzles total time. Similar to how section 3.1 calculates moves, the time taken to solve the easiest five puzzles for the computerized and manual editions are summed together and then values are calculated. A paired t-test demonstrated the average time in seconds for the difficult puzzles was determined to be significantly higher ($p<0.05$) than the average time to solve the easier puzzles ($p=0.0006$). Figure 3

Table 3: Descriptive Statistics of the Time to Solve the Five Easiest Puzzles and the Five Hardest Puzzles. All values recorded in seconds.

Average Time Easy (s)	**Average Time Difficult (s)**
27.83 +/- 20.33	35.96 +/- 20.32
Total Time Easy (s)	**Total Time Difficult (s)**
2782.90	3596.21

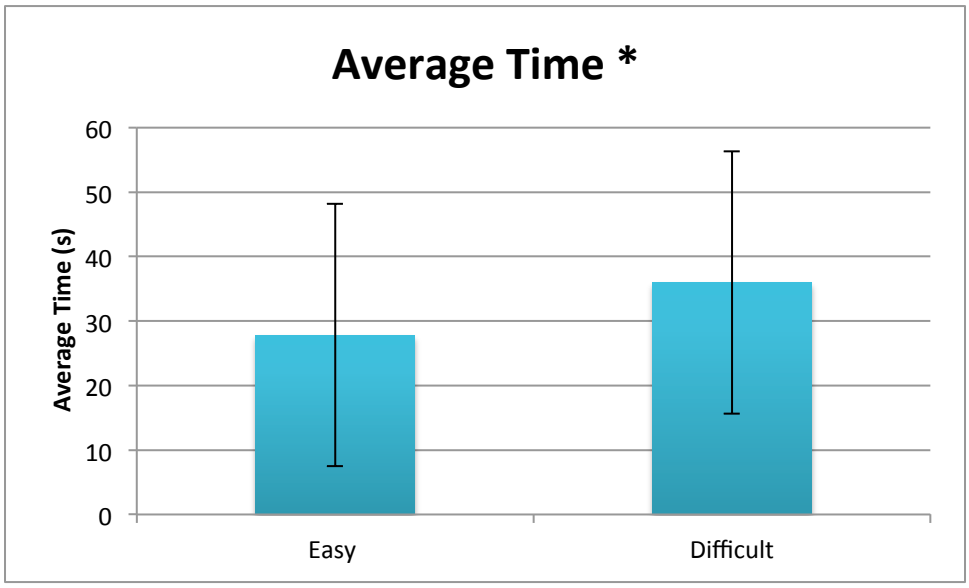

Figure 3: The average time taken to solve the five easiest puzzles compared to the five hardest puzzles. * Indicates that $p<0.05$. $P=0.001$

3.3 Puzzle Difficulty Compared to Relative Oxygenation Concentration in the PFC

Table 4 and figure 4 represent the descriptive statistics for the relative oxygenation concentration levels (in micromolar) of the PFC when solving the easiest five puzzles and the hardest five puzzles. Values for concentration were calculated just as moves and time were calculated in sections 3.1 and 3.2 respectively. Figure 4

demonstrates the discrepancy between the average oxygenation concentration between the easiest puzzles and the hardest puzzles.

Table 4: Descriptive Statistics of the PFC Oxygenation Concentration in the Five Easiest Puzzles and the Five Hardest Puzzles. All values recorded in micromolar.

Average Oxygenation Concentration Easy	**Average Oxygenation Concentration Difficult**
1.65 +/- 1.67	1.82 +/- 1.66
Total Oxygenation Concentration Easy	**Total Oxygenation Concentration Difficult**
164.94	181.67

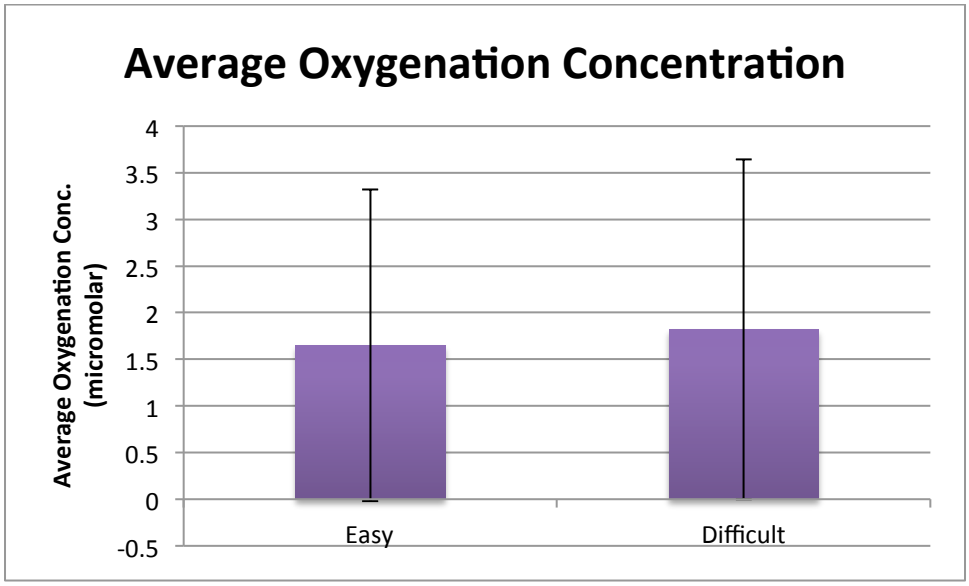

Figure 4: The average PFC oxygenation concentration of the five easiest puzzles compared to the five hardest puzzles. P=0.12

3.4 Discussion

While the numbers of moves and time to solve the hardest five puzzles were shown to be significantly greater than the moves and time for the easiest five, there is no statistically significant difference ($p>0.05$) in the oxygenation level of the PFC in the two scenarios. Since the difference in oxygenation levels was insignificant the study has failed to reject the null hypothesis that states: PFC oxygenation levels will not be higher when doing difficult tasks when compared to easier tasks.

The differences in the number of moves and time to solve being significant ($p<0.05$) demonstrate that the five puzzles considered difficult were indeed more difficult than the five puzzles considered easy. This being significant was necessary for the study to be able to demonstrate that the increased PFC oxygenation was in fact related to puzzle difficulty but unfortunately the data did not confirm that it was. Some important statistics to consider are that the mean of the oxygenation for the difficult puzzles was higher and the p-value was relatively close to being significant. This is important information to recognize because the sample size of this study was fairly small ($n=10$) so more studies should be conducted to determine if these results were slightly skewed. Another important factor to consider with the descriptive statistics of all of the dependent variables (moves, time, and oxygenation) was the fact that the means for the difficult puzzles were less than one standard deviation away from all of the means for its respective counterpart's mean (moves, time, oxygenation of the easy puzzle). This suggests that a greater disparity in puzzle difficulty may actually be necessary.

After reviewing the results of this experiment it was found that the average oxygenation in the easier puzzles was not significantly lower than the average oxygenation in the harder puzzles. However, in this instance, statistics such as mean

oxygenation do not accurately tell the story of what was occurring in a subject's PFC. This hypothesis is based off of PFC activation in a ToL variant that demonstrated differences in PFC activation for simple versus complex tasks. The data in this study may be better described by ancillary analyses. Studies have demonstrated that ancillary analysis can more accurately describe what is occurring in the PFC (12).

First, it must be established that statistics such as mean oxygenation concentration are insufficient metrics. The primary reason that the mean oxygenation concentration is an ineffective measurement is because the intrasubject and intersubject variability was high. For example a subject could take 45 seconds to solve the easy puzzle but only 20 seconds for the difficult puzzle. It is likely that subjects became more efficient as they completed more puzzles but there are also cases where the subject simply "got lucky" or "unlucky" by blindly moving disks. Then when this information was averaged with all subjects it confounds results and cancels out accurate recorded in another subject. For this study it is better to compare individual performance of each subject than to compare overall performance.

In figures 5 and 6 one can see patterns of an increased demand for oxygen in the PFC for the more difficult puzzles. Figure 5 and figure 6 exemplify the hypothesis that a more difficult puzzle will elicit more activation in the PFC. Another important aspect to consider is that there are initially dips in oxygenation values on the more difficult puzzles. These lower values seen in the beginning of difficult puzzles may be a result of the PFC using all of the readily available oxygen. Then the large increases that follow the initial low points are in response to the increased demand. The easy puzzles do not show the dip and therefore there is no subsequent large increase in oxygenation of the PFC.

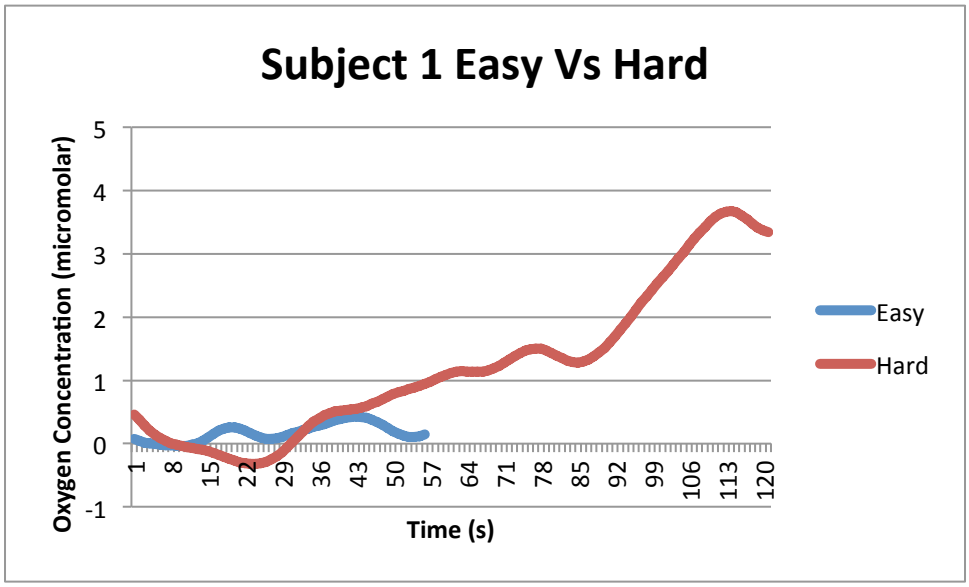

Figure 5: Average oxygenation concentration of subject 1 at all 16 optodes over time for the easiest puzzle and the hardest puzzle.

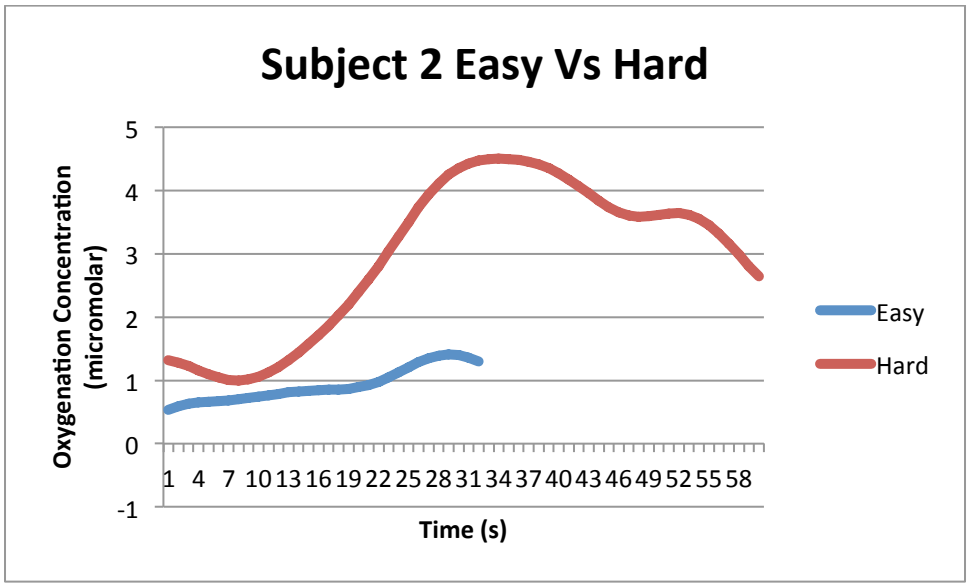

Figure 6: Average oxygenation concentration of subject 2 at all 16 optodes over time for the easiest puzzle and the hardest puzzle.

Also, it should be noted that the relative time differences between the easy and difficult puzzles are much longer for the more difficult puzzle. Per unit time the oxygenation concentrations may not have resulted in a significant difference but the total amount of oxygen used is much different. Unfortunately, the averages conceal what is really occurring.

There were multiple cases where what occurred did not fit the hypothesis that the more difficult puzzles would elicit more oxygenation concentration. Many of these specific cases have anecdotal explanations. Consider the data in figure 7, the subject was notably bad at completing the puzzle. One can see that the time to solve was extremely long for both of the puzzles. The subject never had any real strategy; they just blindly moved disks hoping to get closer to the solution and once they did then were able to solve it with only about 2 disks left. As a result of being so uninvested,

the subject never really activated the PFC because they never implemented any strategic planning. There was no need to think critically since they were just moving disks at random.

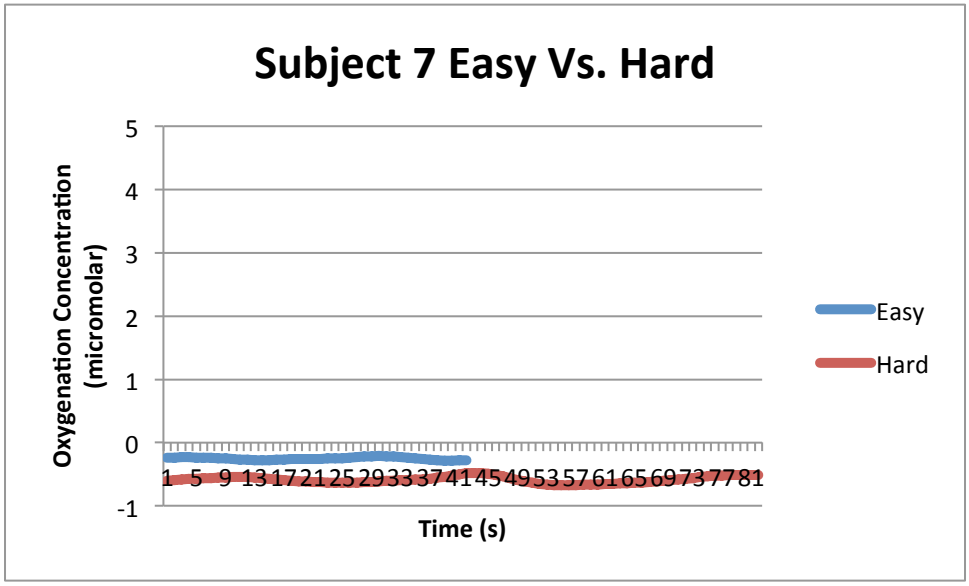

Figure 7: Average oxygenation concentration of subject 7 at all 16 optodes over time for the easiest puzzle and the hardest puzzle.

Next, consider figure 8 where the subject took nearly four times as long to solve the easy puzzle compared to the hard puzzle. Figure 8 demonstrates a case where the subject simply could not figure the easy puzzle out and was "lost". However, the subject didn't have this problem with the harder puzzle. This is an example where the data for the easy puzzle shows that the puzzle was not actually easy for this subject. Since the puzzle was not easy, it increased oxygenation concentration, which then increased average overall oxygenation for the "easier" puzzles. This confounds the data for oxygenation and explains why expected results were not always seen.

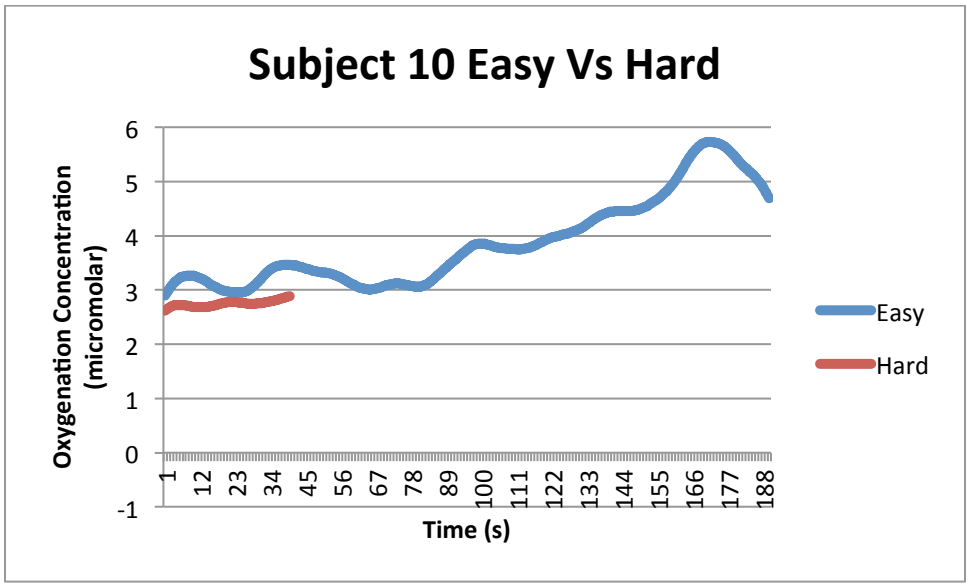

Figure 8: Average oxygenation concentration of subject 10 at all 16 optodes over time for the easiest puzzle and the hardest puzzle.

3.5 Future Directions

While this study didn't have any statistically significant results it did obtain expected results in some cases. What needs to be determined next is why did other cases not yield expected results. The next senior thesis study in the Developmental Motor Control lab pertaining to ToH should address why some of these erroneous results were occurring. Also, another avenue would be to reattempt the study but with specific adjustments to experimental setup.

First, the inclusion criteria should be more scrupulous to control for problem solving ability. This would guarantee that easy puzzles are actually reflected as easy and hard puzzles as hard for PFC activation. Another alternative would be to have the subject rate the puzzle on perceived difficulty after completion. This would show increased oxygenation for an easy puzzle that seemed difficult for a subject that was struggling. The experimenter should increase the disparity between easy and hard

puzzles, which may accentuate the differences in PFC activation and be reflected in the results. Lastly, this study had only 10 participants so a future study could increase the sample size in order to yield more accurate results. These future studies will hopefully demonstrate more difficult tasks require more PFC activation which can open the door to further investigation of how difficult tasks affect DCD.

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