IMPLICIT AWARENESS DURING SKILLED MOTOR LEARNING AND THE IMPLICATIONS FOR REHABILITATION

A Thesis
Presented to
The Academic Faculty

By

Emma Turner

In Partial Fulfillment
of the Requirements for the Degree
B.S. Neuroscience with the Research Option in the
College of Sciences

Georgia Institute of Technology
May 2020

IMPLICIT AWARENESS DURING SKILLED MOTOR LEARNING AND THE IMPLICATIONS FOR REHABILITATION

Approved by:

Dr. Lewis Wheaton, Advisor
School of Biological Sciences
Georgia Institute of Technology

Dr. Timothy Cope
School of Biological Sciences
Georgia Institute of Technology

ACKNOWLEDGEMENTS

I would like to thank Dr. Lewis Wheaton for his guidance and support throughout my time in his research lab. He believed in me and gave me an opportunity to learn and grow so much as a researcher. Without his help this thesis would not have been possible. My time at Georgia Tech would not be the same without him as my advisor and I will be forever grateful.

I wish to express my deepest gratitude to Dr. Regan Lawson for being my mentor when I began working in the lab. She helped me explore so much of the world of neuroscience that helped fuel my drive in all my classes. She not only laid the groundwork and foundation for this entire study but set me up to succeed. I am forever indebted to you for trusting me to continue your work.

Finally, I would like to thank my parents for their encouragement and support throughout my entire Georgia Tech Career.

TABLE OF CONTENTS

ABSTRACT

Motor skills and sequential motor learning are essential in our day to day lives, however, little behind the brain regions involved is known. This means that when someone has a deficiency in their motor skills or their ability to learn motor skills, treatments may not address the actual problem at hand. The purpose of this study is to determine what regions of the brains are active during learning in those who are successful at motor learning and how that differs from those who do not prove to be successful. It was found from examining the electro-encephalography (EEG) data that there were three main areas of the brain that are active during the serial reaction time task (SRTT) that was used to assess the subjects implicit motor learning. These regions were the right precuneus, the right angular gyrus and the right medial frontal gyrus. There war significant difference in these regions between the subject that showed ability to transfer their motor learning and those who were not. These results indicate that there is a difference in brain activation between successful and unsuccessful learners. Better understanding how people learn and the brain regions involved will allow medical professionals to better address those with motor learning deficiencies. This can help lead to the development of more affective treatments.

INTRODUCTION

From birth, we are continuously learning new skills, both consciously and implicitly, and generalizing those skills to become more abled beings. Many of these skills are acquired through motor learning and play crucial rolls in day to day lives from walking to playing your favorite game. Many motor skills are generalizable to other skills, allowing you to use past experiences to build a wide repertoire of skills. The first aim of this study identified an individualized, behavioral indicator for the presence of incidentally developed explicit awareness. The presence of this incidental awareness has been linked to beneficial performance enhancements including movement vigor, as well as improved perceptual sensitivity and generalization [1,2,3]. To continue expanding our understanding of the way in which people learn motor tasks, this aim of the study is to evaluate the effect of this incidentally developed explicit awareness and a subject's working memory on their ability to transfer to a novel, more difficult motor sequence. For example, does learning a skill that is deemed easier, for example walking, help you learn a harder similar skill, like running? A pivotal aspect of motor learning and motor skill acquisition if the ability to generalize or transfer skills from one context to a more complex one.

Remember back to when you were little and learning to ride a bike, a common motor skill that many people have different experiences with. While you may have had a hard time learning to ride, your friend may have learned almost instantly. Now say you and your friend were both given a unicycle, a similar skill yet not the exact same, would your friend learn to ride this faster too? Were they simply better at learning? Did the way at which they went about learning simply prove more rewarding? At the time was their working memory capacity better and allowed them to be more successful? This research aims to look at the way in which those who are successful in generalizing skills and those who are not go about learning motor tasks and how their working memory plays into their success. It is hypothesized that those who are successful in generalizing motor skills use different neural pathways compared to those who are unsuccessful in generalizing skills, in addition, people with a low working memory will be completely hindered from learning the basic motor skill not to mention generalize it.

Working memory is a type of short-term memory that facilitates how we process, use, and remember information.[4] Working memory can be assessed in a number of ways, one of the easiest is an n-back test. This is where subjects are asked to watch a series of pictures on a screen and identify when the current picture matches a picture that was 2 before it. From this you get average response time, percent correct, and a combine score of the two. This study hopes to find a correlation between these results and the outcome for the participant. This is important because sequential motor tasks are everywhere in our lives from putting together a piece of furniture from Ikea to a child playing with Legos: we use sequences of motor movements to accomplish most tasks in our lives. With practice, multiple brain regions work together in a highly complex and slightly unknown manner to accomplish goals. Certain populations, including but not limited to people of older age, those who have experienced stroke, and people with developmental disorders, such as autism, have deficiencies in their abilities to demonstrate sequential motor learning.[5] These deficiencies include lack of coordination, inability to learn motor skills or being able to recall it later, and many more. Not much is known about the neural network controlling this sequential learning besides the general brain areas involved, however, even the interactions between these regions is not fully mapped. Therefore, understanding the neural changes associated with this process in healthy individuals may help provide insights into potential solutions for populations who demonstrate deficiencies. To understand how to help those with deficiencies, we must first understand the systems used in motor learning.

Previous studies, including one of neuroplacticity and its affects on motor skill learning, suggest that there are two parallel processing systems involved in the all aspects of such skills: the implicit and explicit systems.[6] While the implicit system is credited with the optimization of movement execution, the explicit system is more involved with goal selection and execution. The neurobehavioral connection to the results was also explored in these studies. However, some studies' results are conflicting in whether explicit awareness can be detrimental or beneficial to the learning and generalization of motor skills. Beneficial effects that have been found include improved perceptual sensitivity and enhanced movement vigor, especially when awareness developed incidentally. This suggests a potential therapeutic benefit.[7, 8, 9] However, there is a limit in the type of collection this study does by not addressing the individual variability in motor learning.

Motor learning occurs in two separate stages—the fast learning stage and the slow learning stage. In between, there is an intermediate stage, which connects the fast and slow stage. The brain shows activation of dorsolateral prefrontal cortex (dlPFC), posterior parietal regions (PPC), primary motor cortex (M1), supplementary motor area (SMA), basal ganglia striatal regions (BG) and cerebellum (CB) in the first stage.[10] These areas have been linked to two neural networks linked with spatial and motor coordination.[10] The second stage relies more on activation of the cortico-striatal and cortico-cerebellar connections and disengagement of fronto-parietal circuits.[11] This allows execution of movements and the ability to act subconsciously. A common test used to study sequential motor learning, that we also used here, is the SRTT. A SRTT is a motor task that a subject typically completes with their hand and a response pad with keys on it. They use this response pad to respond to a series of stimuli (Figure 1). Unbeknownst to the subjects, the task has a sequence in it, a 7-item sequence and a 10-item sequence, that engages learning in an implicit manner. Thus, this task has proven to be useful in researching a broad range of behaviors, including the cognitive and biological principles of learning and memory.[12]

The subjects partake in a 7 and 10 key sequence because previous studies examining incidental awareness have utilized sequences of 6-8 elements in length, while studies examining motor learning without awareness utilized sequences greater than 10 elements.[13] The assumption with these two sequence lengths is that some people will learn both, while some only learn one. It is highly unlikely that people would learn the 10 key sequence and not learn the prior 7 key. While they are not of main interest to this study, some subjects will fail to learn any of the sequences. Their progress will be tracked by EEG data and reactions times. A 58-channel EEG will be used to record brain activity from all regions and, while certain brain regions are hypothesized to be involved analysis will look at all activity during the experiment. During the study, the reactions time and an individually calculated threshold from the two threshold blocks, informs whether the sequence is learned by the subject or not. Then the data will be examined, and the subjects will be sorted into three groups- the subjects who learn both the sequences (EXP_EXP), the subjects who only learn the 7KEY (EXP_NOEXP), and those who fail to learn either (NOEXP_NOEXP). The EEG data of the EXP_EXP and the EXP_NOEXP will be compared, allowing for an insight into the differences in neural networks being used by the two groups.

The analysis of this data should provide a basis for the exploratory learning that often occurs during rehabilitation. By finding a correlation between working memory and success in the learning and generalization of motor skills a more efficient and customized treatment plan can be developed for those in rehabilitation. Understanding how people go about learning can help inform decisions healthcare providers can make for those who have deficiencies and those who may just not be in a head space to learn a complex task.

LITERATURE REVIEW

Understanding motor control and motor learning will give insight into most day to day activities like writing or playing sports. Most of these actions are sequential and require intricate communication between multiple brain regions. Sadly, some people, who have injuries to these regions, have insufficiencies in motor performance. The most available way to study sequential learning is through a SRTT, in this study it will be a specific variation on this known as a multi-finger sequential task (MFST). Roberts asserts that an SSRT is the best measure of implicit because motor learning typically occurs implicitly and this type of task allows researchers explore the processes underlying a broad range of behaviors, including the cognitive and biological principles of learning and memory.[13] A MFST is just a version of an SRTT that uses multiple fingers to respond on the response pad. This should allow subjects to react faster since they do not need to move their fingers, their fingers can simply rest on the response pad. In this experimental design, subjects react to a visual stimulus of either repeating or non-repeating sequences and are told to press the corresponding key on the response pad that matches the stimuli that appears on the screen. Since this study is concerned with implicit and explicit learning, changes in the number of errors, reaction time to the visual cue, or time required to complete the task will also be recorded. Due to the need for these skills in all cultures and spanning all ages, many other studies have been conducted on neurological responses and behavioral cues during motor learning. While these studies inform the decisions, we made regarding the current study, they also left questions that still need to be answered.

It is known that repetition of an act will lead to improvement, however there is still uncertainty in the most effective way to which approach this repetition. According to Kwakkel's research, along with several other researchers, intensity plays a major role in the effectiveness of repetition.[14, 15, 16, 17] However, Lenze et al's research points out that rehabilitation programs are concerned about the lack of knowledge we have on how intensity affects people's recovery.[18] Increasing the intensity too drastically could prove to be a deterrent due to frustration, on the other hand intensities that are too low lead to boredom Having a better understanding of how a variation of difficulty effects the learning at different stages may help in the development of better rehabilitation or training programs with the maximum effectiveness.

Many studies examine the behavior responses expected during sequential learning. For example, as reported by Savion-Lemieux and Penhune, sequential learning occurs in 3 main stages and in the first fast stage motor learning occurs rapidly.[19] This asserts that changes can be seen by a subject just in one sitting and repeat testing is not needed. Their study also asserts that the second stage, which has been linked with sleep, is more of a consolidation stage. Shadmehr and Holcomb's research provides evidence that the third phase is much longer, and this amount of time correlates with the length of the task.[20] This stage of the learning process is linked with the ability to develop it as an automatic skill. This occurs through the optimization of the timing and kinematics of the subject's performance of the task. Due to the extended nature of the second and third stages, the current study will focus on the first stage as it is easiest to observe.

Other behaviors often associated with motor learning, specifically sequential learning are speed and accuracy of movements during the task. Fritts' law, a predictive model for human movement, states that during motor tasks, there must be a tradeoff between speed and accuracy.[21] The faster someone is acting, the less accurate they will be. This means that a good indicator that learning has occurred is when the speed-accuracy curve shifts in a way that reflects increased speed and increased accuracy. This will allow for a better comparison of results from different level tasks.

Neurological changes are another important aspect the current study hopes to examine, and previous studies inform the expected results or show gaps in knowledge. Recent studies have only begun to examine how the brain functions during many motor tasks. Functional Magnetic Resonance Imaging (fMRI) is commonly used to examine the brain during such tasks and showed that during the fast stage the areas of the brain that looked to be of interest was the dorsolateral prefrontal cortex (DLPFC), primary motor (MI), presupplementary motor areas (preSMA), premotor cortex (PMC), supplementary motor (SMA), parietal, striatum, and cerebellar regions. As reported by Doyon et al., both cortical-cerebellar and cortical striatal loops are used during practice.[22] In addition, striatal pathways are involved more in motivation and performance levels during the learning of the task.[23] These regions are the ones suspected to be involved in motor learning, however the 58 electrode EEG will record data from all brain regions. Once all the EEG data is collected, dipoles or sources of the brain areas that are active in all subjects of a group can be compiled (Figure 2). After compiling the EEG data, event-related potentials (ERPs) clusters are created for each dipole allowing activation of brain regions to be examined. ERPs allow neural activity gathered from EEG to be time-locked to an event, in this case the event is the presentation of the stimulus.[24] Due to their event-related presentation of data, it allows data to be seen divided by trial and organized by reaction time. This allows neural activity to be seen relating to the reaction time and how it may change as a reaction gets faster. This could occur both when a subject gets used to the paradigm but also when implicit awareness occurs.

While no study has directly tested what the current study is examining, many had experimental techniques that informed our design. Savion-Lemieux and Penhune proved that there is a difference between motor learning for musicians and non-musicians.[19] Therefore the current study will not use subjects with more than 3 years of formal musical training. Nissen and Bullemer designed the SSRT task that the current study uses the MFST variation of. Savion-Lemieux and Penhune also used a series of stimuli in their experiment and found that the optimum time between stimuli is 750 ms, allowing the subject to respond any time while the image is on the screen.[19]

The current study will examine the ability of subjects to implicitly learn a repetitive sequential motor task. Utilizing an EEG and the response times from the SSRT task, the subjects awareness of the pattern and their mastering of it will be tracked. This will allow us to break the subjects into the explicit learners who become aware of the pattern and learn it and those who never become aware and learn the pattern. After completing the 7-key task, the subjects will move forward to the 10-key, allowing us again to see who will learn this pattern. In the end there will be 3 groups: those who learn neither the 7 or 10-key, those who learn the 7 but do not learn the 10, and those who learn both. By doing this we will be able to track the parts of the brains the groups used and see if how the different groups approached the task influences their ability to learn.

METHODS AND MATERIALS

Subjects

This experiment looks to collect data on motor learning during sequential motor tasks from 18-35-year-old right-handed non-musicians. Subjects first participated in an Edinburgh Handedness Inventory to assess the level of handedness along with a short questionnaire regarding any previous musical training they had received.[25] Only subjects with a handedness score greater than 0.6 (indicating right hand dominance), and less than 3 years of formal musical training, were eligible to participate in the study.

Working Memory Assessment

Upon arrival, the subjects' working memory was assessed. A test known as an n-back test, specifically the 2-back test, was used. From this test the percent correct, average time, and a combined score were recorded. This will later be used to assess if there is a minimum threshold of working memory required to have successful sequential motor learning.

Experimental Paradigm

The next, longest part of the experiment, is the serial reaction time task(SRTT). It requires a 58-electrode electroencephalogram (EEG) cap, a 4 key response pad, and a PsychToolbox program used to make the visual stimuli. The participants are unaware that the SRTT includes two patterned sequences. The program calculates threshold data for each participant's baseline reaction times during a priming block and uses that to assess a z-score for each block of the sequence. 1 block of the sequence involves 7 repetitions of the sequence. The 7-key sequence is repeated by every participant for 20 blocks. After this, another random sequence priming block is done to reassess changes in the participants reaction threshold before the 10-key sequence. The participant then performs this sequence for up to 30 blocks. The number of blocks they complete is determined by the participant's performance in learning the sequence. Learning is classified as a z-score of -1.85 or lower twice in a row. This type of score shows a reaction time indicative of knowing what was coming, no longer reacting to the stimuli. Once they show this z-score or lower twice or after 20 blocks, whichever occurs first, another priming block occurs and then they are asked if they noticed a sequence and if they did they are asked to recall the it.

Statistical Analyses

Based on a subject's individual performance they were classified into either EXP, NONEXP or EXP_NOEXP. EXP subjects had explicit behavior on the 7-key sequence and explicit recall on the 10-key sequence. NONEXP subjects showed no explicit behavior on the 7-key sequence and non-explicit recall on the 10-key sequence. EXP_NOEXP subjects had explicit behavior on the 7-key sequence, but non-explicit recall on the 10-key sequence. The data collected from the individual subjects were analyzed using a MATLAB program known as EEGLab. The EEG data were epoched into each individual block. Their average accuracy and z-scores were calculated and used for in-group comparisons. During the 10-key sequence there is no set number of blocks completed by the subjects, so the fastest block, in the case of EXP_NOEXP, or block where learning was established, for EXP, was used for analysis. This allowed neural activation around the time of learning to be compared. EEGLab was used to find the dipoles in the brain that are active in different participants at different times of the study. By grouping the participants into EXP and EXP_NONEXP lets the dipoles active for the entire group to be analyzed. The event related potentials (ERPs) of specific regions, for each group were analyzed to compare how the region was active or inactive in relation to the stimulus or button push (Figure 3). EEGLab has built in statistics tools to show if the activation of the region in the two groups is statistically different.

RESULTS

Behavioral Results

Motor learning depends on many regions of the brain as well as outside factors. Upon completion of the experiment the first thing that had to be done to make any meaning of the results was to separate the subjects into the 3 groups, EXP_EXP, EXP_NONEXP and NONEXP_NONEXP. Thirty subjects ended up participating in this study. Of those thirty, nine stood as the control group, nine learned both the 7 and 10 key blocks and were classified as EXP_EXP, five only learned the first block and were classified as EXP_NONEXP, and the remaining 7 leaned neither block and were classified as NONEXP_NONEXP.

EEG Results

The first data collected from subjects was information about their working memory. The scores from the n-back assessment show that the more successful the subject was at the learning the lower their score (Figure 2). The EXP_EXP and EXP_NONEXP showed more similar scores than that of the NONEXP_NONEXP group.

Throughout this experiment, there is a neural difference shown in the ERP movement locked images between the successful and unsuccessful groups in 5 main brain areas. The first area explored was the precuneus (Figure 3), which includes Brodmann area 7. The successful group displayed both a stimulus-locked and movement- locked negative feedback, while the unsuccessful group had greater stimulus-locked positive feedback. In this region of the brain, there is the largest statistical significance ($p<0.05$) between these two groups 250 ms after onset of the stimulus. This significance being concentrated after this time period suggests a difference in response of the brain after the movement.

The mean dipole and ERP movement-locked image for the right angular gyrus (Figure 4), which includes Brodmann area 3, shows major significance between the successful and unsuccessful groups in a linear, stimulus locked fashion, around 200 ms. This area of the brain is used minimally by the successful group, while the unsuccessful group has a very strong, stimulus-locked negative-feedback right at 200 ms.

Activity in the right medial frontal gyrus (Figure 5) shows strong significant difference between the two groups at about 200 ms. The successful group shows slight stimulus related negative-feedback at this time while the unsuccessful shows strong stimulus-locked positive-feedback. The unsuccessful groups reaction is highly stimulus locked and very strong.

CONCLUSION AND FUTURE WORK

Behavioral Analysis

Behavior and environment play a key role in brain function. Your ability to learn is easily influenced by outside factors such as stress, sleep, food and much more. All of these things have also been shown to also directly affect a person's working memory. Through this study and the results gathered from a n-back working memory assessment, a direct correlation can be seen between a subject's working memory and their success in the motor learning paradigm (Figure 2). While we don't know the direct cause or relationship between the two, the data suggests that at a certain point, if your working memory is hindered enough, a subject will be unable to perform any meaningful motor learning.

EEG Analysis

By conducting this experiment, it was clear that the successful and unsuccessful groups had some level of difference in how their brains, specifically in five areas, functioned during and after the learning of the 7-key test. The precuneus (Figure 3) is shown to be responsible for highly integrated tasks, including visuo-spatial imagery, episodic memory retrieval and self-processing operation. This area also includes Brodmann area 7, the secondary sensorimotor cortex, that assists in visuospatial processing, working memory, and tactile localization. When the ERP movement locked Image cluster was run on the cluster that included this region, cluster 3, there was a statistically significant difference in their function after ~250 ms. The location and trend of these results depicted in Figure 3 suggest that the successful group is reacting both int stimulus-locked fashion, but also in a movement-locked fashion, while the unsuccessful group is just heavily stimulus-locked. Another difference between the groups is that the successful group shows negative feedback, while the unsuccessful has feedback which is negative. All of this suggests that the successful group is taking in both the optic inputs from the pictures on the screen, but also the tactile, sensory feedback from their hands and other senses. Due to the stimulus -locked nature of the unsuccessful group it can be assumed that the unsuccessful group is heavily replying on their processing of the stimulus and forsaking their other senses.

The next part of the brain that showed differences between the two groups was the right angular gyrus (Figure 4), which includes Brodmann area 3. This region is attributed with spatial cognition, memory retrieval, attention, as well as housing part of the primary somatosensory cortex. This cortex assists in the subject’s finger proprioception and motor learning. While the successful group shows little pattern or really heightened activity in this region, the unsuccessful group had a very powerful, stimulus-locked negative deflection right at 200 ms. This is congruent with the findings that the unsuccessful group is relying and reacting only to the stimulus, which is localized in this region due to its spatial cognition function.

The last region of interest between these two groups is the right medial frontal gyrus (Figure 5). This region serves as a filter system to help individuals select incoming sensory information that is relevant. It helps with motor learning, sequencing and planning, as well as working memory and visuo- spatial and motor attention. Both the successful and unsuccessful groups have stimulus locked feedback in this region, however the statistical significance and region on the graph of importance is before the successful subjects showed learning (faster reaction times) and between 100 and 200 ms. The successful group had slight negative feedback, while the unsuccessful group had very weak negative feedback followed by a very strong positive feedback. This suggests subjects who are unsuccessful use more brain power and attention in this region that is heavily focused on the stimulus.

Overall, all of these findings suggest that the way the subjects went about learning primed them to be able to be successful or not. Successful subjects seems to rely on all of their sensory inputs especially feedback after the movement, while the unsuccessful subjects relied far too heavily on just the inputs and feedback of the stimulus.

Future Work

While this experiment shed light on how learning occurs and what helps make someone successful at it, there are many things that can further our knowledge on this subject. The first thing that would help shed insight would be simply collecting data from more subjects. At this point we can see trends, but even with the parts that are statistically significant, it isn't enough to draw solid conclusions. Adding more people to the subject clusters will help make more distinct conclusions. It would also be helpful to add analysis of the EEG data of those people who did not learn either of the sequences. This could help show what areas totally unsuccessful learners are using, maybe allowing us to shed light on if there is a way to train your brain to become a better learner. Finally, I think it would be interesting to have those who did not learn either block the first time come in for another testing day. I think this could help show how and to what extent working memory changes. If the subjects were given more clear instructions prior to this second day, "make sure you get 8+ hours of sleep and eat a good mean before you come", there could be an in subject comparison done between the two days.

FIGURES

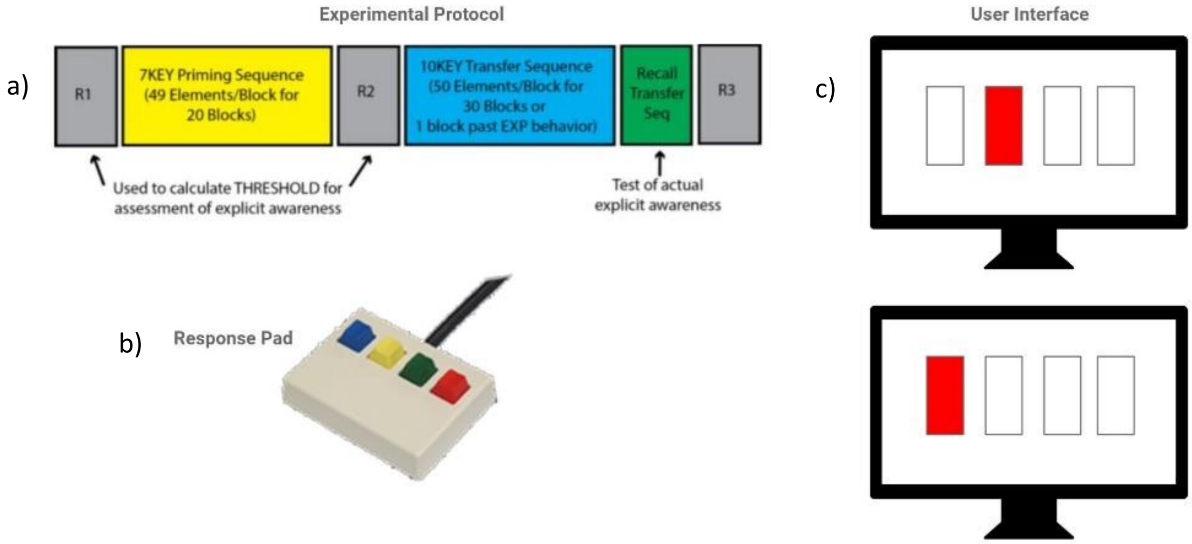


Figure 1. Experimental Design and Set Up. a) Generalization of protocol for priming subjects. Subjects received a sequence to determine threshold followed by a 7KEY priming sequence. They then experienced another threshold block followed by a 10KEY transfer sequence. They were then asked to recall the 10KEY sequence to test explicit awareness. b) 4-key response pad used during experiment. c) example of how the stimuli are presented to the subject.

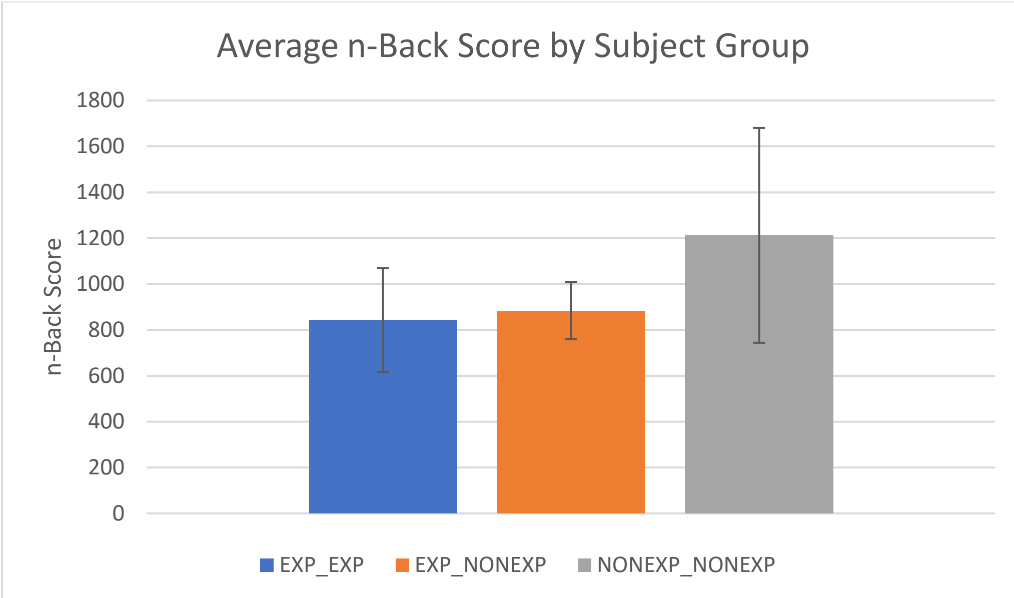


Figure 2. Average n-Back score by subject group. EXP_EXP had the lowest average of the 3, while NONEXP_NONEXP had the highest average of the 3.

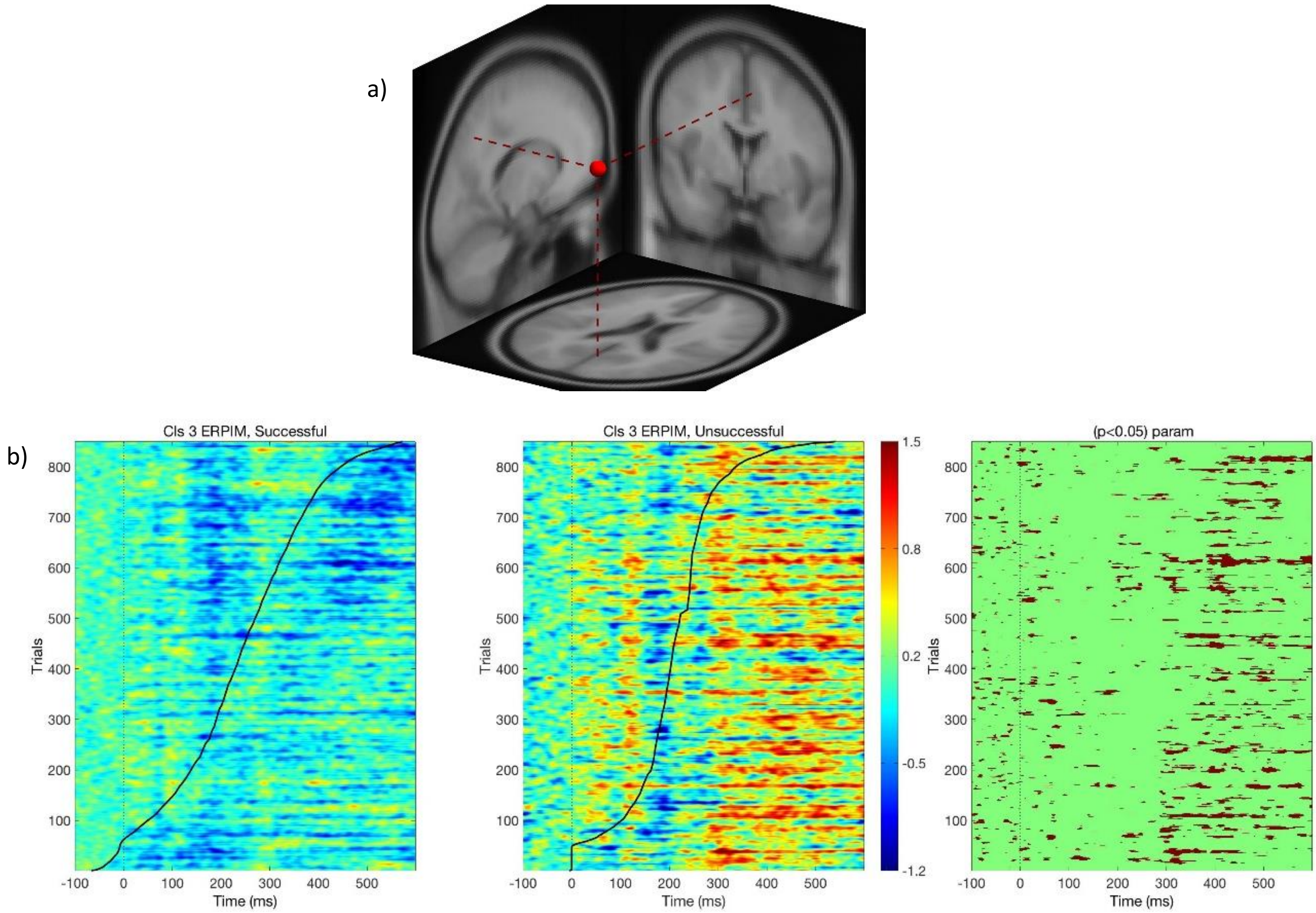


Figure 3. a) The mean dipole for subjects in cluster 3 that shows a location in right precuneus that includes Brodmann Area 7 b) ERP movement-locked image clusters from an EEGLAB STUDY comparison between subjects in cluster 3 and a time vs trials graph showing where statistical significance is between the successful and unsuccessful subjects. The third graph shows the statistical significance ($p<0.05$) between the successful and unsuccessful subjects.

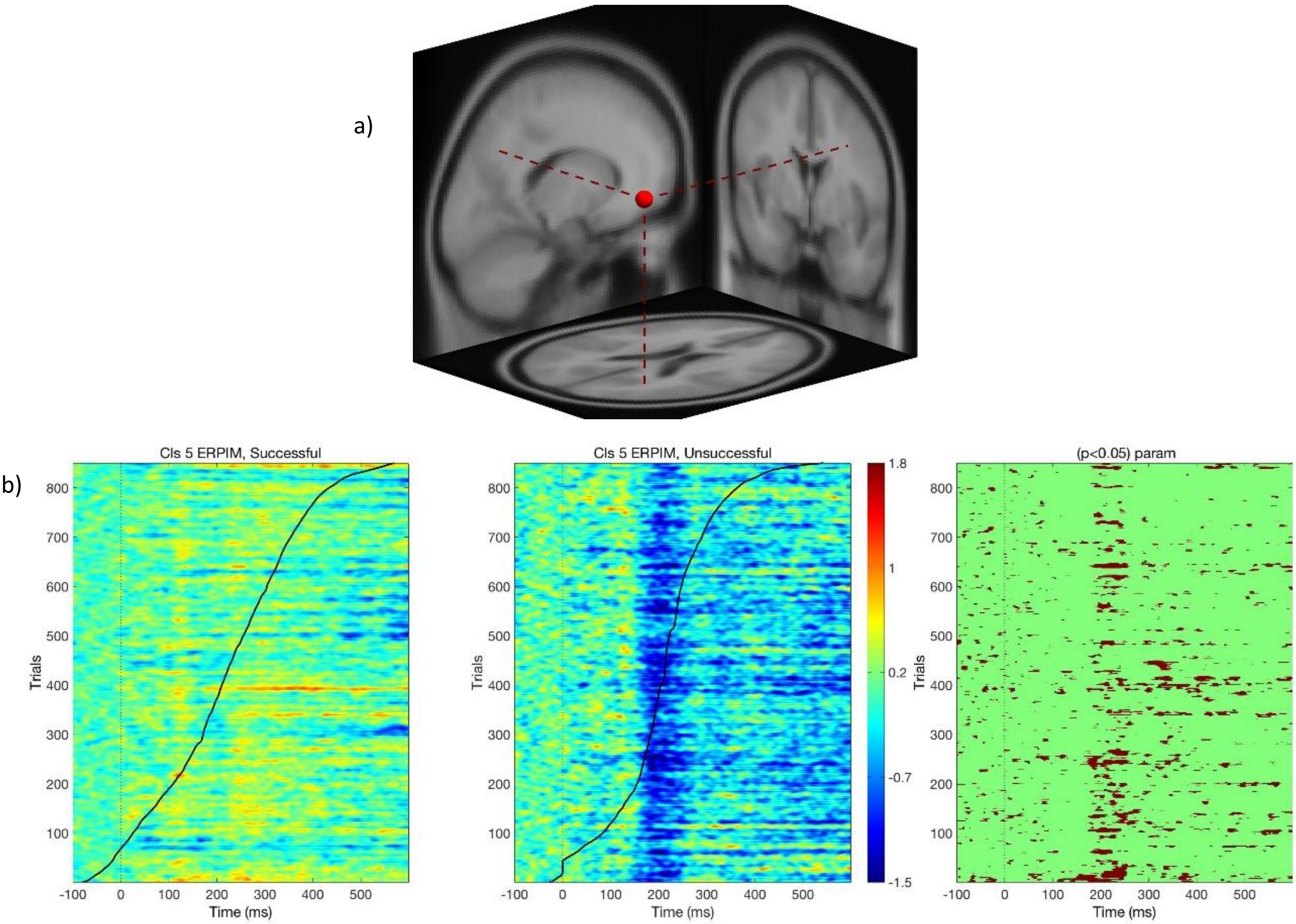
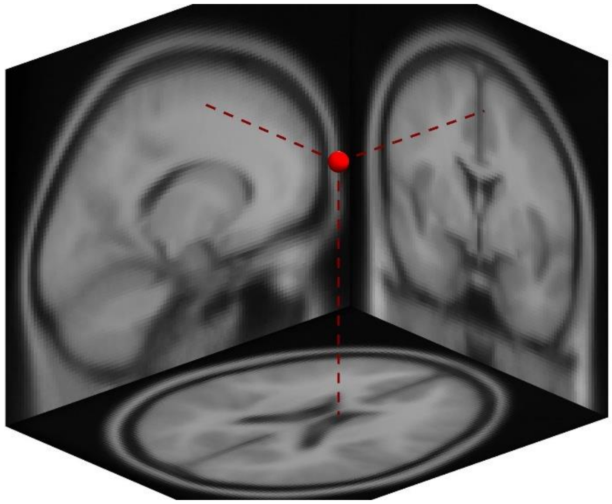


Figure 4. a) The mean dipole for subjects in cluster 5 that shows a location in Right angular gyrus that includes Brodmann Area 3 b) ERP movement-locked image clusters from an EEGLAB STUDY comparison between subjects in cluster 5 and a time vs trials graph showing where statistical significance is between the successful and unsuccessful subjects. The third graph shows the statistical significance ($p<0.05$) between the successful and unsuccessful subjects.

a)



b)

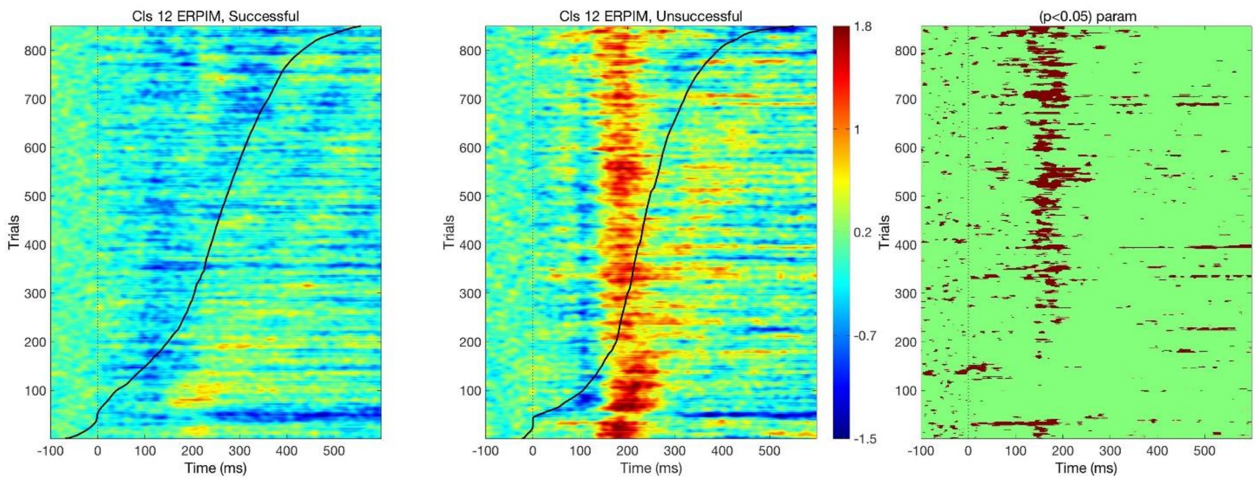


Figure 5. a) The mean dipole for subjects in cluster 12 that shows a location in Right Medial Frontal Gyrus that includes Brodmann Area 6 b) ERP movement-locked image clusters from an EEGLAB STUDY comparison between subjects in cluster 12 and a time vs trials graph showing where statistical significance is between the successful and unsuccessful subjects. The third graph shows the statistical significance ($p<0.05$) between the successful and unsuccessful subjects.

REFERENCES

1. M.Rose, H.Haider, and C.Buechel, "The emergence of explicit memory during learning," Cerebral Cortex, vol. 20, no. 12, pp. 2787–2797, 2010.
2. J. R. Wessel, H. Haider, and M. Rose, "The transition from implicit to explicit representations in incidental learning situations: More evidence from high-frequency eeg coupling," Experimental Brain Research, vol. 217, no. 1, pp. 153–162, 2012.
3. J. Laubrock and A. Kinder, "Incidental sequence learning in a motion coherence discrimination task: How response learning affects perception," Journal of Experimental Psychology Human Perception and Performance, vol. 40, no. 5, pp. 1963–1977, 2014.
4. R. Jacobson. "What is Working Memory?" https://childmind.org/article/what-is-working-memory/. Accessed September 30, 2019
5. J. H. Howard, D. V. Howard, N. A. Dennis, and A. J. Kelly, "Implicit learning of predictive relationships in three-element visual sequences by young and old adults," Journal of Experimental Psychology-Learning Memory and Cognition, vol.34, no.5, pp.1139–1157, 2008.
6. E. Dayan and L. G. Cohen, "Neuroplasticity subserving motor skill learning," Neuron, vol. 72, no. 3, pp. 443–454, 2011.
7. S.N. Meissner, A. Keitel, M. Sudmeyer, and B. Pollok, "Implicit motor sequence learning and working memory performance changes across the adult life span," Frontiers in Aging Neuroscience, vol. 8, 2016
8. J. A. Taylor and R. B. Ivry, Implicit and Explicit Processes in Motor Learning, ser. Action Science: Foundations of an Emerging Discipline, pp.63–87.
9. J.A.Taylor,J.W.Krakauer,and R.B.Ivry,"Explicit and implicit contributions to learning in a sensorimotor adaptation task," Journal of Neuroscience, vol.34, no.8, pp.3023–3032, 2014.
10. O. Hikosaka, K. Nakamura, K. Sakai, and H. Nakahara, "Central mechanisms of motor skill learning," Current Opinion in Neurobiology, vol. 12, no. 2, pp. 217–222. 2002.
11. V. S. Huang, A. Haith, P. Mazzoni, and J. W. Krakauer, "Rethinking motor learning and savings in adaptation paradigms: Model-free memory for successful actions combines with internal models," Neuron, vol. 70, no. 4, pp. 787–801, 2011.
12. E. M. Robertson, "The Serial Reaction Time Task: Implicit Motor Skill Learning?"The Journal of Neuroscience, vol. 27, no.38, pp. 10073-10075. 2007.
13. M.Rose,H.Haider,andC.Buechel,"Theemergenceofexplicitmemoryduringlearning," Cerebral Cortex, vol. 20, no. 12, pp. 2787–2797, 2010.
14. G. Kwakkel, "Impact of Intensity of Practice after Stroke: Issues for Consideration." Disability and Rehabilitation, vol 28, pp. 3-14. 2006.
15. J. A. Nugent, K. A. Schurr, and R. D. Adams. "A Dose-Response Relationship between Amount of Weight-Bearing Exercise and Walking Outcome Following Cerebrovascular Accident." Archives of Physical Medicine and Rehabilitation, vol.75, no.4, pp.399-402. 1994.
16. H. Woldag, et al. "Is the Repetitive Training of Complex Hand and Arm Movements Beneficial for Motor Recovery in Stroke Patients?" Clinical Rehabilitation, vol 17, no.7, pp. 723-730. 2003.

17. K. Kawahira, et al. "Addition of Intensive Repetition of Facilitation Exercise to Multidisciplinary Rehabilitation Promotes Motor Functional Recovery of the Hemiplegic Lower Limb." Journal of Rehabilitation Medicine, vol. 36, no.4, pp. 159-164. 2004.
18. E. J. Lenze, et al. "Significance of Poor Patient Participation in Physical and Occupational Therapy for Functional Outcome and Length of Stay." Archives of Physical Medicine and Rehabilitation, vol 85, no. 10, pp. 1599-601. 2004.
19. T. Savion-Lemieux, V. B. Penhune. "The Effect of Practice Pattern on the Acquisition, Consolidation, and Transfer of Visual-Motor Sequences." Experimental Brain Research, vol. 204, no.2, pp 271-281. 2010.
20. R. Shadmehr, and H. H. Holcomb. "Neural Correlates of Motor Memory Consolidation." Science, vol. 277, no.5327, pp. 821-25.1997.
21. I. S. MacKenzie. Fitts' law. In K. L. Norman & J. Kirakowski (Eds.), Handbook of human-computer interaction, pp. 349-370. 2011.
22. J. Doyon, et al. "Functional Anatomy of Visuomotor Skill Learning in Human Subjects Examined with Positron Emission Tomography." European Journal of Neuroscience, vol 8, no 4, pp. 637-48. 1996.
23. M. Liljeholm, and J. P. O'Doherty. "Contributions of the Striatum to Learning, Motivation, and Performance: An Associative Account." Trends in Cognitive Sciences, vol 16, no. 9, pp. 467-75. 2012.
24. S. J. Luck, Introduction to the Event-Related Potential Technique, 2nd Edition, ser. Introduction to the Event-Related Potential Technique, 2nd Edition, pp. 1–406, Times Cited: 286 Luck, SJ, ISBN: 978-0-262-52585-5.
25. R. C. Oldfield, "The assessment and analysis of handedness: The edinburgh inventory," Neuropsychologia, vol. 9, no. 1, pp. 97–113, 1971.