The Differences in Spatial Memory between 2D and 3D Maze Environments

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Abstract
Spatial memory refers to the pathways in the brain that are needed to plan routes to specific locations and remembering where an object is located. This allows humans to use information about their environment to form a model of that environment with instructions on how to navigate it. To do so, the brain integrates sensory information with a map of the environment, to give information about how to traverse it. This experiment investigates whether spatial memory can be transferred between 2D and 3D environments using the Rey-Osterrieth test and *Minecraft*. It uses one-way ANOVA tests, a two-sample t-test, a Product Moment Correlation Coefficient, and Linear Regression to explore the relationships between different factors on the time taken and errors made in completing the maze. Despite having a small sample size, this project shows a statistically significant positive correlation between a participant's Rey-Osterrieth score and the number of errors they make on a particular maze. This shows some evidence that spatial memory can be transferred between 2D and 3D environments because of this correlation, but there must be more statistical tests carried out to prove this. These tests include ones that analyze larger datasets, and could shed light on teen hippocampal activity and how spatial memory manifests and is transferred specifically within teen brains.

Keywords
Spatial Memory, Neuroscience, Statistics, *Minecraft*, Rey-Osterrieth.

1. Introduction
The purpose of this study is to explore the differences in spatial and working memory between 2-dimensional and 3-dimensional environments and whether spatial memory is transferred between the environments. A transfer in spatial memory between such environments can be characterized by an improvement in time taken or reduction in errors made while navigating a 3D environment, after having successfully completed a two-dimensional task.
Ekstrom, Kahana, and Fried have investigated the pathways in which spatial memory travels (Ekstrom et al. 2003). They found that cells that help navigate spaces (mainly located in the hippocampus) and cells that respond to landmarks (mainly found in the parahippocampal region) have complementary roles, meaning that spatial memory is composed of multiple parts and can be used to navigate virtual environments. The link between video games and spatial cognition has been explored by Spence and Feng (Spence, Feng 2010) for applications in teaching young children about spatial awareness and navigating spaces. They theorize that certain types of video games help improve spatial cognition, which helps verify the methodology for this particular study. The relationship between playing Minecraft and hippocampal activity has been explored by Clemenson, Henningfield, and Stark (Clemenson et al. 2019). They conclude that navigating a *Minecraft* world is correlated with improvements in hippocampal activity outside of the game. This means that in a three-dimensional maze, there should be higher hippocampal activity, meaning that the participant is actively using their spatial memory. Cockburn and McKenzie have evaluated spatial memory and visuospatial awareness in 2D and 3D physical and virtual environments (Cockburn, McKenzie 2002), which could have applications in machine learning and artificial intelligence. They assert that spatial memory actually deteriorates when subjects are introduced to a three-dimensional environment rather than a two-dimensional one. However, this effect was observed for sparse retrieval tasks, and it does provide some evidence that spatial memory can work in both 2D and 3D environments. Burgess, Maguire, and O'Keefe have shown that the hippocampus is essential to spatial learning by using an environment in virtual reality that tests (Burgess et al. 2002). They assert, from both their VR environment and their images of the hippocampus, that the hippocampus has roles in navigating complex environments and remembering the positions of the objects. The study done by Burgess et al. provides evidence that the hippocampus is the site of certain types of spatial memory pathways that are important to this particular study. These five studies help set the ground for this particular one, which aims to illustrate how spatial memory is transferred between 2D and 3D environments, i.e. between a template and a physical or virtual environment. Spatial memory is an essential field of study since studying it shows how neurons in certain areas of the brain work together to form maps of the environment and how they aid us in traversing these maps, especially in a virtual world like *Minecraft*. This model could theoretically be used to aid drivers, especially new ones, in driving more safely on roads by providing them with a two- and three- dimensional template of a road, which could then

simulate traffic conditions. This model would allow drivers to navigate the "maze" of traffic on a road safely and effectively.

2. Experimental Design

This study assessed how spatial memory is transferred within and between 2D and 3D maze environments. It used the game *Minecraft* for the 3D maze since it has incorporated an element that requires spatial memory and virtual awareness. The mazes were designed to serve as an equivalent to an environment that the brain could integrate with certain sensory information from that environment. The experimenter measured participants' time taken to complete each maze and the number of errors that they made per maze. In this experiment, an error on either maze is defined as making a wrong turn or otherwise going the wrong direction. The experimenter aimed to test for the presence or absence of hippocampal activity in the brain, which would allow them to see if there was active use of spatial and working memory.

2.1. Rey-Osterrieth Test

My experiment measures the activity of these areas in spatial and working memory with the Rey-Osterrieth Complex Figure Test (Rey-O), as seen in Figure 1 below. It is a neuropsychiatric test that tests a participant's spatial memory by asking them to copy down a complex figure on paper, then tests their working memory by prompting them to recall that same figure 10-15 minutes later (Shin et al. 2006). It is scored out of 36 points and participants are asked to correctly identify and draw 18 design elements as part of a figure. Two points are awarded for a correctly placed and correctly drawn element, one point is awarded for where the element is either correctly drawn or correctly placed, and zero points are awarded if the element is unrecognizable or absent from the participants' reproduction of the figure. Working memory is one of the types of memory used in navigating a maze since there is information given to the brain that needs to be immediately stored. This particular test is important since it involves navigating a complex two-dimensional space, which can be used as a measure of whether spatial memory gets transferred into a three-dimensional environment.

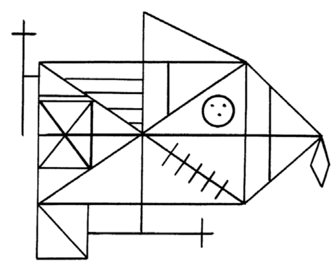

Figure 1: The Rey-Osterrieth Complex Figure.

2.2. Maze Design

This project used the video game *Minecraft* to create and mimic a two-dimensional maze and a three-dimensional maze for participants to navigate. The two-dimensional maze was an overhead image of the maze in *Minecraft* and administered one to each of the participants of the experiment. The three-dimensional maze was a 48x48 maze with four quadrants and other obstacles in between. Playing the video game involves navigating 3D spaces on a 2D screen, therefore testing one's working and spatial memories.

1. Participants were given numerical IDs to preserve their anonymity.
2. The time taken to complete any one maze was measured with a stopwatch and recorded in a data table. If any one participant took more than five minutes to complete a maze, they were discounted from the experiment as they would provide a large outlier.
3. An error on either maze is defined as making a wrong turn or otherwise going the wrong direction. If a participant made more than eight (8) errors on a maze, they could provide an outlier and were therefore discounted from the experiment.

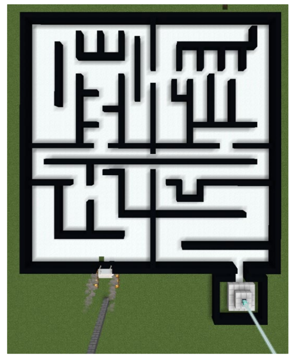

Figure 2: The maze which was used in the experiments. This image was given as the 2D maze, and participants were required to traverse this maze in the game for the 3D maze.

2.3. Hypotheses

- H_0 = There is no difference between the time taken or number of errors for a 2D maze, for a corresponding 3D maze, and for traversing the 3D maze a second time.
- H_1 = There is a difference between the time taken or number of errors for a 2D maze, for corresponding 3D maze, and when doing the 3D maze twice.

2.4. Sampling Techniques

20 people from ages 13-17 in this experiment were sampled; particularly this age group since these were people closest to the legal age of driving, a skill which requires the use of both spatial and working memory. 20 random numbers were picked randomly out of the participant IDs. Some confounding variables could have been that the participants were all self-motivated, middle to high income, and all from Southern California. These 20 people were divided into four groups with five people in each group. The control groups were those whose participants did either a 2D maze twice or a 3D maze twice since these groups are not subject to a 2D template of the maze that may help them on the 3D maze (they are subject to either one). The experimental groups were those whose participants did the 2D maze then the 3D maze, or vice-versa.

The experimenter conducted a survey that had questions such as "On a scale of 1 to 10, how good do you say you are at *Minecraft*?" or "Have you played any other video games?" to assess participants' experience with *Minecraft* or other video games. They used the survey to assess if there were any blatant outliers in the time taken to complete the maze or in the number of errors, and they would eliminate that outlier and re-sample to fit the original sample size. Thus, they controlled for many confounding variables (see above), that could lead to a spurious result in this experiment.

3. Data and Statistical Analysis

In this experiment, the experimenter used parametric methods, namely one-way ANOVA tests and unpaired two-sample t-tests, the Product Moment Correlation Coefficient, and Model 2 Regression, because the sample data lay on a ratio scale.

3.1 Data Presentation

The mean time for the 2D maze across the three groups was 22.3 seconds with a standard deviation of 7.92 seconds and a variance of 62.7 seconds. The low standard deviation and variance indicate that the distribution of data points is clustered tightly around the mean. The median was 21 seconds, and the modes for the 2D time are 18, 21, and 25 seconds. The mean of the data set is slightly greater than the median, so the distribution for times on the 2D maze could have a slight positive skew.
The mean time for the 3D maze across the three groups was 112.5 seconds with a standard deviation of 61.6 seconds and a variance of 3799.1 seconds. The high standard deviation and variance indicate that the distribution is not clustered tightly around the mean and is therefore less reliable. The median was 91 seconds, and the modes for the 3D time is 240 seconds (4 minutes). The mean of the data set is greater than the median, so the distribution for times on the 2D maze could have a positive skew. However, these values of 240 seconds are outliers to the distribution of times.

After eliminating them, the new mean is 92.9 seconds with a standard deviation of 36.2 seconds and a variance of 1307.7 seconds. Again, the variance and standard deviation are high, but lower than that of the distribution with the outliers included. This means that the distribution without outliers provides a better estimate of actual population values than the distribution with outliers.

3.2 One-Way ANOVA Test and Unpaired Two-Sample t-tests

In the test for whether prior experience with a particular maze helps with the 2D or 3D mazes, as depicted in Figures 2 and 3, the experimenter chose to use the one-way ANOVA test to compare the averages of all three groups and unpaired two-sample t-tests to compare the averages of two groups at a time. The Null Hypothesis is that the median difference between the average times it takes a group to complete the maze based on experience with any prior mazes is zero. The alternative hypothesis is that there is a significant difference between the average maze times of the groups.

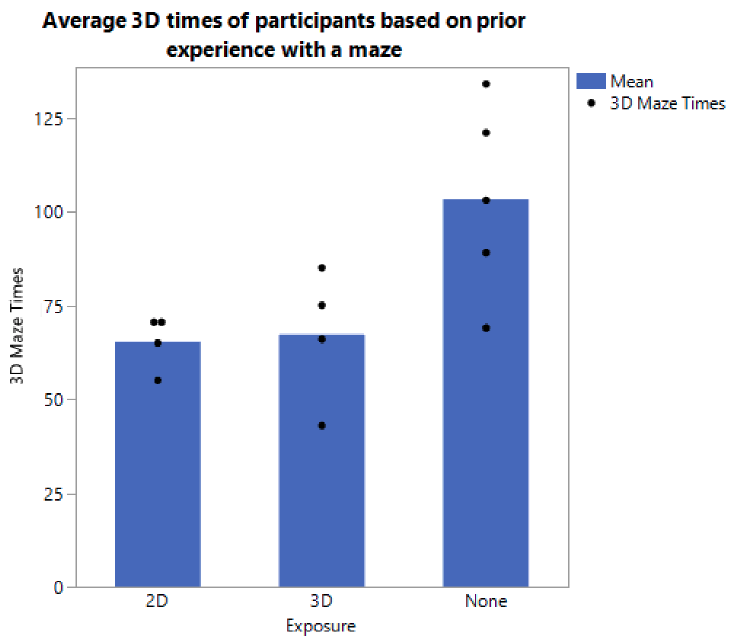

Figure 3a: Participants' experience with a maze vs. the time it took their group to complete the 3D maze.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
None	2D	37.95000	13.01167	2.2813	73.61870	0.0375*
None	3D	35.95000	13.01167	0.2813	71.61870	0.0483*
3D	2D	2.00000	13.71550	-35.5981	39.59811	0.9884

Figure 3b: Ordered differences report for the Tukey-Kramer HSD test.

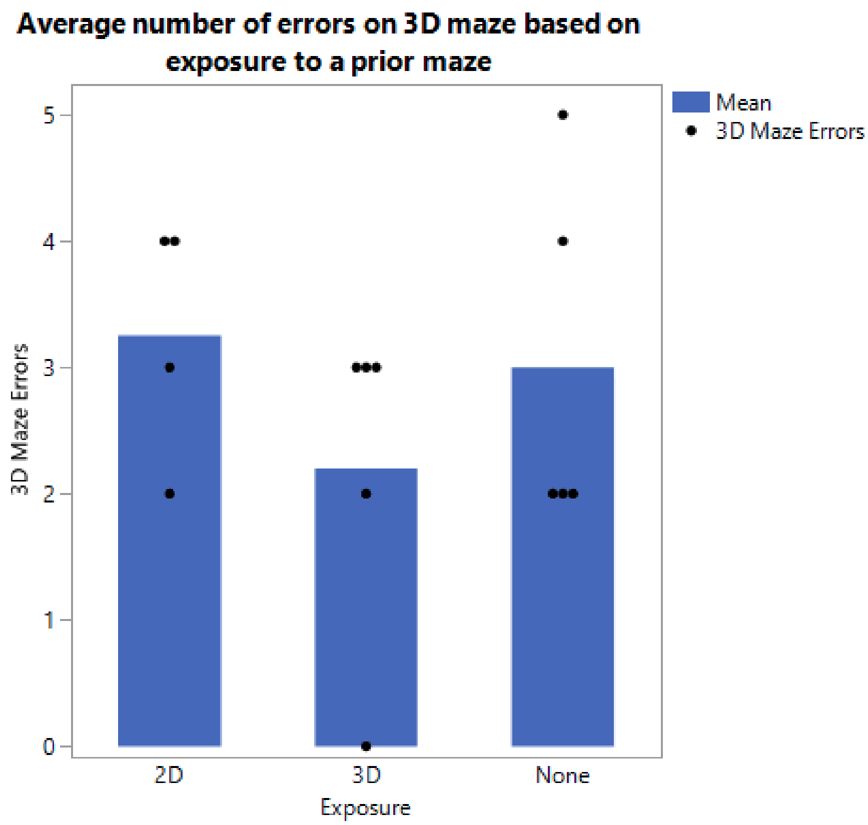

Figure 4: Participants' experience with a maze vs. the number of errors their group made on the 3D maze.

The F-value for the first case, as depicted in Figure 3a, is 5.59 when comparing all three groups. When compared to the F-distribution for one-way ANOVA, this value is statistically significant. The two-tailed p-values for comparing the averages of each of the groups is 0.023, which is also statistically significant. Therefore, we reject the null hypothesis and state that the group without experience on any maze takes significantly longer than other groups to complete the 3D maze. Since there is a statistically significant result, there is a warrant to analyze the differences between each of the groups with the Tukey HSD test. The results of that test are shown in Figure 3b, where there is a significant difference between the mean time of the inexperienced group and the mean time of the group with 2D maze experience. A similar result is shown between the mean 3D maze times of the inexperienced group and the group with 3D maze experience. However, there is no significant difference in the mean 3D maze time for the 2D-exposed and 3D-exposed groups, meaning that the 2D task works just as well as the 3D task as a template for the 3D environment.

The F-value for the second case (see Figure 4), which was the test for if the participants took less time on the 3D maze given prior maze experience, was 0.880, and the p-value was 0.44. This value is also not statistically significant at df=2 since it is under the critical value of 5.99 at the 0.05 threshold. Therefore, we accept the null hypothesis that there is no difference between the average times it takes a group to complete the 3D maze based on experience with any previous maze. This means that prior maze solving experience in this experiment does not affect the number of errors made on this 3D maze.

3.3 Two-Sample T-test

The second test was for whether participants who did the Rey-O Recall test in preparation for the 3D maze took less time on it. The experimenter chose to use an unpaired two-sample t-test to compare the mean times of participants who took the Recall test before their 3D against the times of those who did not.

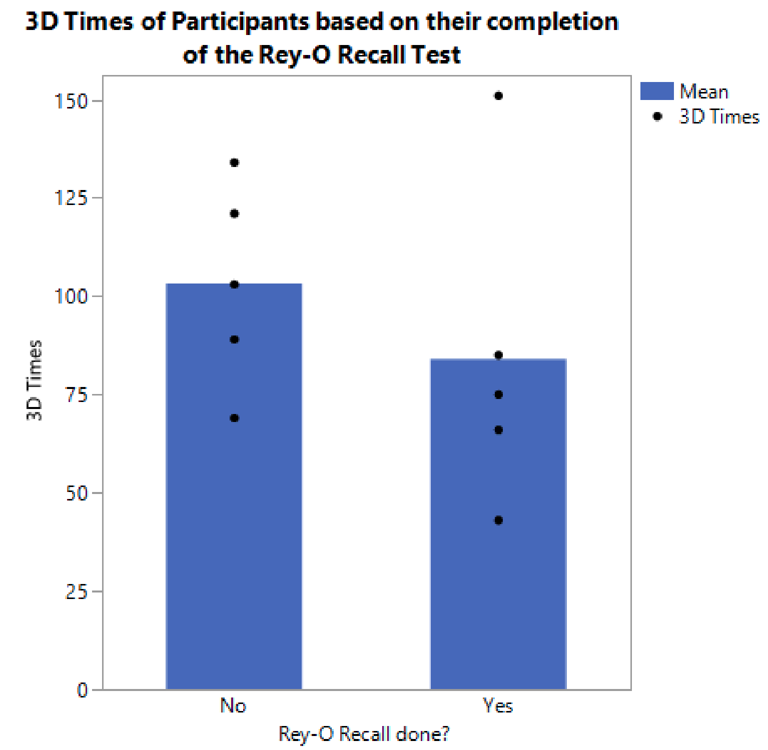

Figure 5: The times of participants on the 3D maze based on if they did the Rey-O Recall test before that 3D maze. (with outlier)

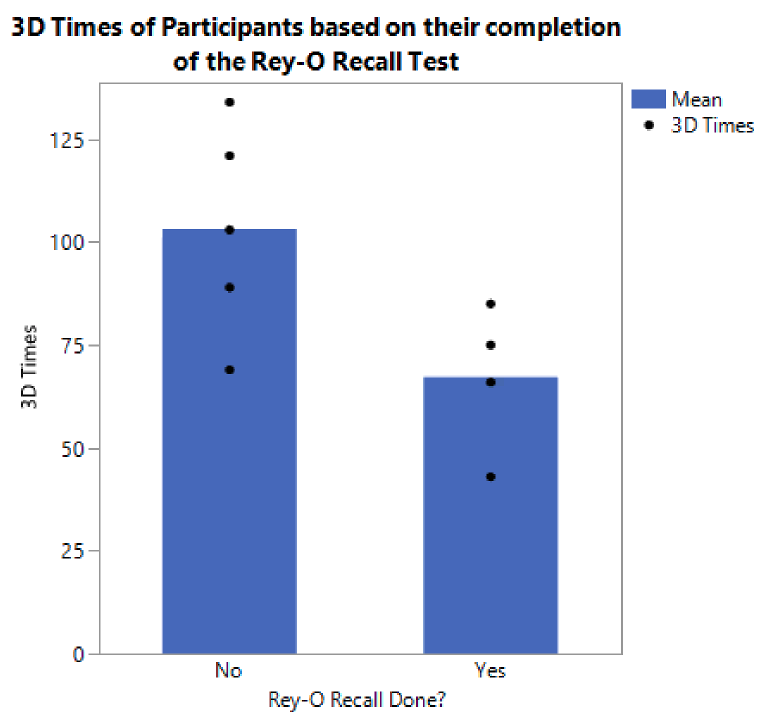

Figure 6: The times of participants on the 3D maze based on if they did the Rey-O Recall test before that 3D maze. (without outlier)

In these results, there seems to be a trend that people who did the Rey-O Recall took less time on the 3D maze than did people who did not do the Rey-O Recall before the 3D maze. However, there was an outlier. Figure 5 is the graph with the outlier of (Yes, 151 s.), meaning that someone who did the Rey-O Recall took 151 seconds to complete the 3D maze. With the outlier, the t-statistic is 0.895 and $p = 0.399$. This is not statistically significant, so this data in Figure 5 would suggest that there is no difference between the mean 3D maze times of participants regardless of whether they did the Rey-O Recall or not. Figure 6 has the same data, except that the outlier was eliminated. The experimenter chose to eliminate it since the participant had reported themselves as not very experienced in video games and their time was above the time limit of the 3D maze. In Figure 6, the t-statistic is 2.36 and $p = 0.0503$. This is not a statistically significant result, but there still seems to be a trend where those who did the Rey-O Recall test took less time to complete the 3D task. To have a better understanding of whether this trend is representative, this two-sample t-test should be repeated with more data points.

3.4 Product Moment Correlation Coefficient & Model 2 Regression

The third test was for whether the participants who got better Rey-O scores would take less time and make fewer errors on the 3D maze than the first time they did the maze (see figures 4 and 5). This test used both the Product Moment Correlation Coefficient and Model 2 Regression. Model 2 Regression was the appropriate test since neither of the variables, the Rey-O Recall score (ind. var) and difference in time or errors (dep. var) were under experimenter control and there was no evidence that one variable causally depended on the other. The null hypothesis for both the Product Moment Correlation Coefficient test and Model 2 Regression would be that there is no correlation between the score on the Rey-O test and the error and time improvements. The alternative hypothesis is that there is a statistically significant correlation between the participants' Rey-O score and their improvement in the time and errors on the maze.

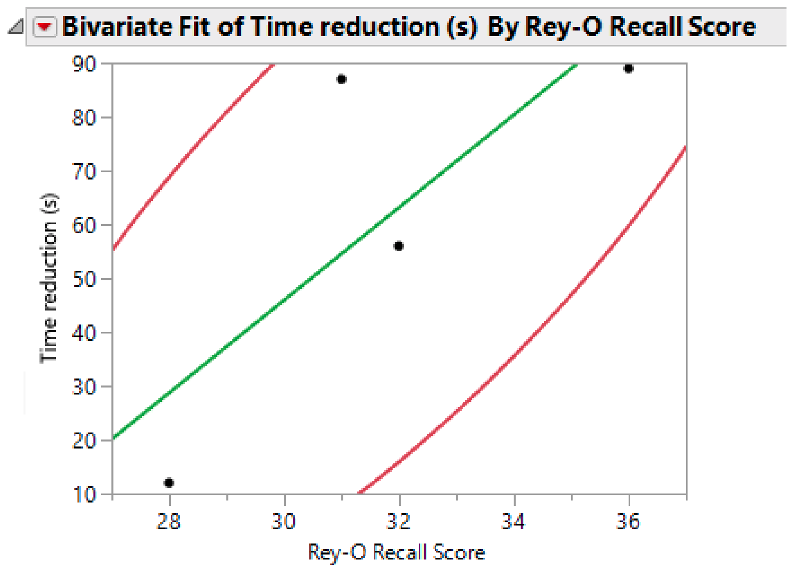

Figure 7: The time improvement of participants who did the 3D maze twice based on their score on the Rey-O Recall test.

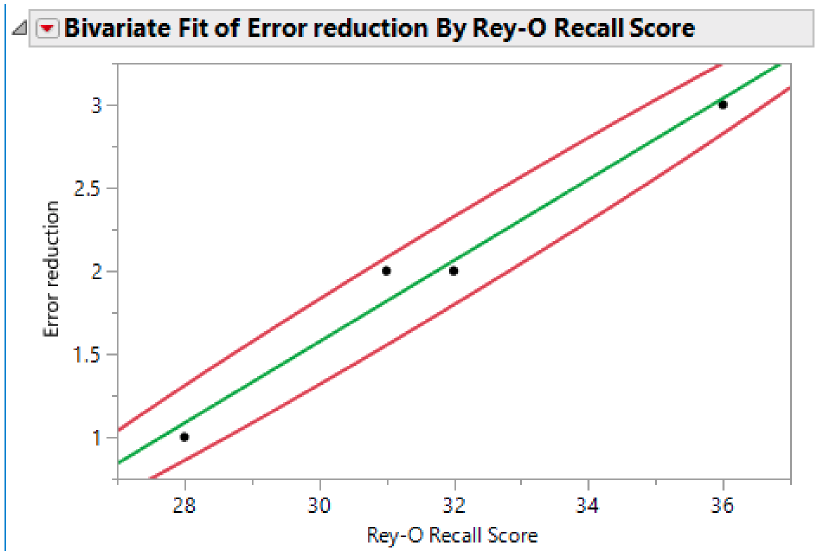

Figure 8: Difference in errors between the first 3D maze and second 3D maze in participants in the 2D-3D group based on their Rey-O Recall score.

These tests were used to investigate how the Rey-Osterrieth Recall score affects both the difference in time taken for the first and second attempts and the difference in errors made between the first and second attempts. In the Time reduction by Rey-O Recall Score, the r-value from the Product Moment Correlation Coefficient was 0.7905 and the r^2 value was 0.6249. Since the sample size was small, these values could not be compared to any critical value, so the results for these tests are not statistically significant. Therefore, the null hypothesis that there is no correlation between the Rey-O score and a participant's improvement in time fails to be rejected. In the test for improvement in errors made, the r-value was 0.9885, the r^2 value was 0.9771, and the p-value was 0.0115. Since the p-value is less than 0.05, the null hypothesis that there is no correlation between the Rey-O score and the improvement on the maze by the number of errors made can be safely rejected. This means that if someone gets a higher score on the Rey-O Recall test, they will probably make fewer errors the second time they complete the maze.

4. Conclusions

This experiment explored whether memories of 2D environments transferred to similarly designed 3D environments to find out whether 2D and 3D environments can aid teenagers in navigating 3D spatial memory tasks.. It was conducted because understanding activity in the hippocampus as related to spatial memory transfer between 2D and 3D environments is important in determining whether 2D templates are reliable in aiding navigation of 3D environments. The experiment finds that 2D and 3D tasks prepare teenagers about equally well, but better than not completing any task, for navigating three-dimensional spatial environments. This result supports the original hypothesis by demonstrating a statistically significant difference between the mean times of the group without prior maze experience and the groups with experience. The significant difference between the mean 3D task time of groups that have preparation with a maze and the group that did not, along with how there is not a difference between the mean time of the group with 2D vs. 3D preparation, shows that both 2D and 3D task experience could improve the time taken to complete a 3D task. Regardless of the Rey-O score, both 2D and 3D maze experience could improve completion times in 3D spatial environments. This experiment also correlates performance on the Rey-O test, in 2D, with a reduction of errors in the completion of the 3D maze. Since a 2D test followed by a 3D maze shows an error reduction on that 3D maze, there is evidence that using 2D maps to navigate 3D spaces is neuroscientifically reasonable. There is in fact evidence of a transfer in spatial memory between 2D and 3D maze environments because the Rey-Osterrieth, a two-dimensional test, was correlated with a reduction of errors made in a three-dimensional environment. Although the sample size of this study is not large, the positive correlation makes a case for how there is a transfer in spatial memory between two-dimensional and three-dimensional environments. Therefore, we can infer that a 2D template like the Rey-Osterrieth Complex Figure test can provide a logically integrated environment that is similar to a real environment that the brain can use to give the person information about their orientation, heading, and important landmarks. Since the Rey-Osterrieth is a measure of spatial memory, and since participants with higher Rey-O scores traversed a *Minecraft* task with fewer errors, certain elements in

Minecraft could also serve as a measure of spatial intelligence. Therefore, three-dimensional models, like *Minecraft* or virtual reality, can be used to teach or aid new teenage drivers in numerous tasks relating to navigating roads. To verify this, more reliable data must be collected and more statistical tests must be applied to that data.

5. Improvements to the Study and Future Research

This study can be improved by increasing the sample size, and therefore the number of participants in each condition. With a larger sample size, more reliable results can be derived, such as stronger correlations (if they exist) or a causal relationship between two variables. The experiment can also incorporate multiple regression tests based on a participant's prior maze experience and their Rey-O recall score to observe the differences between time taken to complete (or errors made in) the first and second mazes. In this experiment, the test was only for whether there was a transfer or difference in spatial memory between two-dimensional and three-dimensional environments. In a future experiment, there could be a model that investigates what exactly that model is and how pathways in the hippocampus and entorhinal cortex behave in both types of environments. Potentially, fMRI could be used for this experiment because it isolates certain parts of the brain in an image and colors them based on their activity, which is measured in changes associated with blood flow. One such expected result of a future experiment would be to see the dentate gyrus and entorhinal cortex be colored since those two areas contain special types of neurons that orient a person in their environment and give them a heading of where they are going. If fMRI or MRI was either inaccessible or imprudent to use in a future study, an electroencephalogram (EEG) could be used to detect frequencies of brain waves coming from certain parts of the brain. One expectation for an experiment with the EEG would be higher frequencies in the dentate gyrus and entorhinal cortex for the same reasons listed above. It would also be interesting to observe how this would change if we moved the 3D maze from a game environment to a virtual reality environment. Since grid and place cells are essential to giving information about where the person is oriented and their current route, a virtual reality maze could increase the firing rate of those neurons or otherwise affect their neural pathways since the person is oriented in an environment that is more representative of the real world. This project serves as an investigation into spatial memory, its pathways within the brain, and its uses in experimentation. Future projects using the techniques and improvements discussed above will be able to provide a basis for stronger claims about the nature of how spatial memory differs between two-dimensional and three-dimensional environments and a wider range of potential applications. These future projects could have applications in improving the safety of drivers on the road.

6. Acknowledgements

I would like to acknowledge Hamsi Radhakrishnan, Dr. Craig Stark, and Dr. Michael Yassa from the UC Irvine Center for the Neurobiology of Learning and Memory for help in developing this project and conducting statistical analysis. I would also like to thank Dr. Joshua Beattie from the Stanford Online High School for his guidance and advice in reviewing this paper.

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8. Biography

Siddhant Karmali, a rising sophomore at the Stanford University Online High School, has won awards for work on projects in biomimetics and biophysics involving how a biologically inspired machine can follow a route. He has also won fourth place at the regional Brain Bee competition in 2020. He is currently on a water polo team and has won a silver medal at the Junior Olympics during the 2019 season.

9. Appendix

1. Karmali, Siddhant. "Videogames Survey". 14 March 2020, https://docs.google.com/document/d/1nxuzVqNMbAScsYsBoAR4xJKuU2GCp6MPHgqJlx7tbJ4/edit?usp=sharing. This is the survey that I gave out to my participants during the experiment.