# An Investigation into how the Structure of Brain Regions involved in Mindfulness Meditation Affects Function

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*"One of the most remarkable characteristics of Sherlock Holmes was his power of throwing his brain out of action..."*
*-Dr. Watson*

**Introduction**

Mindfulness is a concept that originates in Buddhism and consists of the development of a particular kind of attention, one that is characterized by a nonjudgmental awareness, openness, curiosity, and acceptance of internal and external present experiences.[1]

For more than two thousand years, mindfulness meditation has been practiced as a means of achieving a state of self-awareness. More recently, however, it has been shown that cultivating a more mindful way of being is associated with less emotional distress, more positive states of mind, and a better quality of life.[2] In addition, mindfulness practice can influence the brain, the autonomic nervous system, stress hormones, the immune system, and health behaviors, including issues as diverse as depression[3], irritable bowel syndrome[4], chronic pain[5], and addiction[6–8] in beneficial ways.

As a result, mindfulness meditation has recently become the subject of intensive scientific research.[1-8] One of the main research goals is to determine which brain regions and networks mediate the cognitive aspects of meditation. There is now accumulating evidence to suggest that attentional brain regions are involved in many meditative practices.[9-11] This is not surprising since it has previously been shown that most meditation practices require some amount of focused attention and/or executive mental functions.[12] However, there has not been as much agreement on which regions are active during mindfulness meditation between studies, as one would expect.[13]

Associating which brain regions are active to the practice of mindfulness meditation will provide a better understanding of the function of these brain regions and the networks involved. Applying this information, could allow for new methods that would induce neuroplastic changes that mediate positive outcomes.

**Problem Statement**

The question that this project aims to address is how severely the structure of brain regions involved in mindfulness meditation affects the amount of neural activity that occurs between regions among experienced mindfulness meditators and controls.

**Resolution**

In order to address this concern, data was needed to analyze. Unfortunately, much difficulty was encountered while searching for publicly available data, in regards to mindfulness meditation or even meditation in general. Fortunately, after countless hours of searching, two data sets were found in the form of correlation matrices.

The first data set was obtained from "Impact of meditation training on the default mode network during a restful state" by Taylor et al.[14] This study examined the effect of mindfulness training on the resting state functional connectivity (rsFC) within the Default Mode Network (DMN). The resting state data were collected from 13 meditators (over one thousand hours of experience) and 11 beginner meditators (no prior experience, but were trained for 1 week prior to the study) using functional magnetic resonance imaging (fMRI). Pairwise correlations and partial correlations were computed between the DMN seed regions' time courses and were compared between groups utilizing a Bayesian sampling scheme. These pairwise correlation and partial correlation matrices were the data that were used to address the problem statement.

The second data set was obtained from "Meditation-State Functional Connectivity (msFC): Strengthening of the Dorsal Attention Network and Beyond" by Froelinger et al.[15] There is little known regarding the effects of meditation on other resting-state networks. As a result, the goal of this study was to investigate the effects of meditation experience and meditation-state functional connectivity (msFC) on not only the DMN, as Taylor had done, but on multiple resting-state networks (RSNs). Mindfulness-meditation practitioners performed two 5-minute scans, one during rest and one while meditating. The control group, with no meditation experience, underwent one resting-state scan. Exploratory regression analyses for the relationships between years of meditation practice and rsFC were conducted. These regression data were the data used, along with the Taylor data, to better address the problem statement.

Based on the availability of data, the question was addressed in the following manner. The locations of brain region centers (seed regions used that were known to be involved in mindful meditation) were varied to determine the affect on the amount of neural activity that occurs between brain regions as a function of the Euclidian distance between region centers.

It was hypothesized that the locations of brain regions would, in fact, greatly affect the amount of neural activity between regions. It is also hypothesized that the original locations of these region centers would create one of the least amounts of neural activity possible in the DMN, compared to random arrangements. It is also believed that the locations of region centers will more severely affect the neural activity in experienced meditators over non-meditators.

## Methods

*To analyze the data, MATLAB and the Brain Connectivity Toolbox[16] were used.*

Taylor Data

First, the coordinates of the seed regions within the Default Mode Network were inputted into MatLab, which were derived from the human atlas of Talairach and Tournoux (1988) as shown in Table 1. A three-dimensional plot was created to visualize the correlations, shown in Tables 2 and 3, between the brain regions along with the weights of the correlations as seen in Figures 1 and 2. This was performed by implementing a pre-existing file and revising it to function in three-dimensions.[17] Both the inexperienced and experienced meditator correlation and partial correlation matrices were also inputted and plotted, as seen in Figures 3-6.

**Table 1. Coordinates for seed regions within the default mode network**

| Region | BA | *x* | *y* | *z* |
|---|---|---|---|---|
| PC/PCC | 31 | 8 | −53 | 27 |
| DMPFC | 10 | −10 | 57 | 19 |
| VMPFC | 10 | −2 | 47 | −10 |
| R IPL | 39 | 48 | −56 | 27 |
| L IPL | 39 | −40 | −67 | 34 |
| R ITC | 21 | 56 | −4 | −22 |
| L ITC | 21 | −56 | −10 | −17 |
| R PHG | 36 | 26 | −32 | −15 |
| L PHG | 36 | −26 | −29 | −18 |

*Notes*: Stereotaxic coordinates are derived from the human atlas of Talairach and Tournoux (1988), referring to the medial–lateral position (*x*) relative to the midline (positive = right), and anterior–posterior position (*z*) relative to the commissural line (positive = superior). Designations of Brodmann position (*y*) relative to the anterior commissure (positive = anterior), and superior–inferior areas for cortical areas are also based on this atlas. BA = Brodmann area; PCC = posterior cingulate cortex; PC = precuneus; DMPFC = dorso-medial prefrontal cortex; VMPFC = ventro-medial prefrontal cortex; IPL = inferior parietal lobule; ITC = inferolateral temporal cortex; PHG = parahippocampal gyrus; R = right; L = left.

**Table 3. Correlation matrix between nodes of the default mode network for experienced (blue) and beginner meditators (yellow).**

| *Regions* | PC/PCC | DMPFC | VMPFC | R IPL | L IPL | R TC | L TC | R PHG | L PHG |
|---|---|---|---|---|---|---|---|---|---|
| PC / PCC | | 0.41 (0.03) | 0.44 (0.03) | 0.53 (0.03) | 0.54 (0.03) | 0.29 (0.03) | 0.29 (0.03) | 0.24 (0.27) | 0.27 (0.03) |
| DMPFC | 0.37 (0.03) | | 0.53 (0.03) | 0.25 (0.03) | 0.54 (0.03) | 0.29 (0.03) | 0.29 (0.03) | 0.24 (0.04) | 0.27 (0.03) |
| VMPFC | 0.45 (0.03) | 0.40 (0.03) | | 0.25 (0.03) | 0.35 (0.03) | 0.39 (0.03) | 0.33 (0.03) | 0.06 (0.04) | 0.11 (0.04) |
| R IPL | 0.65 (0.02) | 0.34 (0.03) | 0.32 (0.03) | | 0.44 (0.03) | 0.26 (0.04) | 0.23 (0.04) | 0.17 (0.04) | 0.16 (0.04) |
| L IPL | 0.47 (0.03) | 0.29 (0.03) | 0.29 (0.03) | 0.53 (0.03) | | 0.24 (0.04) | 0.26 (0.04) | 0.19 (0.04) | 0.24 (0.04) |
| R TC | 0.31 (0.03) | 0.18 (0.03) | 0.27 (0.03) | 0.27 (0.03) | 0.13 (0.04) | | 0.52 (0.03) | 0.18 (0.04) | 0.19 (0.04) |
| L TC | 0.32 (0.03) | 0.29 (0.03) | 0.27 (0.03) | 0.27 (0.03) | 0.17 (0.04) | 0.53 (0.03) | | 0.12 (0.04) | 0.25 (0.03) |
| R PHG | 0.22 (0.03) | -0.10 (0.04) | -0.02 (0.04) | 0.16 (0.03) | 0.12 (0.04) | 0.20 (0.04) | 0.14 (0.04) | | 0.51 (0.03) |
| L PHG | 0.23 (0.03) | -0.01 (0.04) | 0.01 (0.04) | 0.17 (0.04) | 0.16 (0.04) | 0.22 (0.03) | 0.27 (0.03) | 0.54 (0.03) | |

**Table 2. Partial correlation matrix between nodes of the default mode network for experienced (blue) and beginner meditators (yellow).**

| *Regions* | PC / PCC | DMPFC | VMPFC | R IPL | L IPL | R TC | L TC | R PHG | L PHG |
|---|---|---|---|---|---|---|---|---|---|
| PC / PCC | | 0.13 (0.04) | 0.21 (0.03) | 0.35 (0.03) | 0.27 (0.04) | -0.002 (0.04) | 0.03 (0.04) | 0.11 (0.04) | 0.09 (0.04) |
| DMPFC | 0.11 (0.04) | | 0.36 (0.03) | -0.001 (0.04) | 0.21 (0.04) | -0.013 (0.04) | 0.15 (0.04) | -0.18 (0.04) | -0.01 (0.04) |
| VMPFC | 0.27 (0.03) | 0.23 (0.03) | | -0.05 (0.04) | 0.04 (0.04) | 0.22 (0.04) | 0.05 (0.04) | 0.001 (0.04) | -0.03 (0.04) |
| R IPL | 0.47 (0.03) | 0.09 (0.04) | -0.05 (0.04) | | 0.20 (0.04) | 0.10 (0.04) | 0.03 (0.04) | 0.03 (0.04) | -0.04 (0.04) |
| L IPL | 0.14 (0.04) | 0.09 (0.04) | 0.09 (0.03) | 0.32 (0.03) | | -0.003 (0.04) | 0.02 (0.04) | 0.05 (0.04) | 0.09 (0.04) |
| R TC | 0.05 (0.04) | -0.03 (0.04) | 0.13 (0.04) | 0.09 (0.04) | -0.07 (0.04) | | 0.42 (0.03) | 0.10 (0.04) | -0.002 (0.04) |
| L TC | 0.06 (0.04) | 0.17 (0.03) | 0.06 (0.04) | 0.03 (0.04) | -0.03 (0.04) | 0.43 (0.03) | | -0.05 (0.04) | 0.16 (0.03) |
| R PHG | 0.12 (0.04) | -0.14 (0.04) | -0.06 (0.04) | 0.02 (0.04) | 0.02 (0.04) | 0.09 (0.04) | -0.04 (0.03) | | 0.47 (0.03) |
| L PHG | 0.07 (0.04) | -0.04 (0.04) | -0.08 (0.04) | -0.02 (0.04) | 0.07 (0.04) | 0.04 (0.04) | 0.18 (0.03) | 0.48 (0.03) | |

Next, it was assumed that the correlations shown in Tables 2 and 3 correspond with the increase or decrease in connections between brain regions. These data were then multiplied by the distance between brain region centers using the locations from Table 1, creating a metric that would roughly represent the increase or decrease in the amount of neural activity across the distance between regions. Summing these metrics would then represent the total neural activity of either experienced or inexperienced meditators as seen in Table 4. Then, the locations of the brain regions were randomly switched with one another for all possible permutations, and the metric of total neural activity across the distance between regions was calculated for each random permutation. These permutations were then sorted and plotted, which can be seen in Figures 7-10. The pairwise correlation values were also plotted, in Figures 11 and 12, to see how they compare with one another.

Froelinger Data

The same methods that were applied to the Taylor data were applied to the Froelinger data, the correlation between the meditators and control group for rsFC.

**Results**

Taylor Results

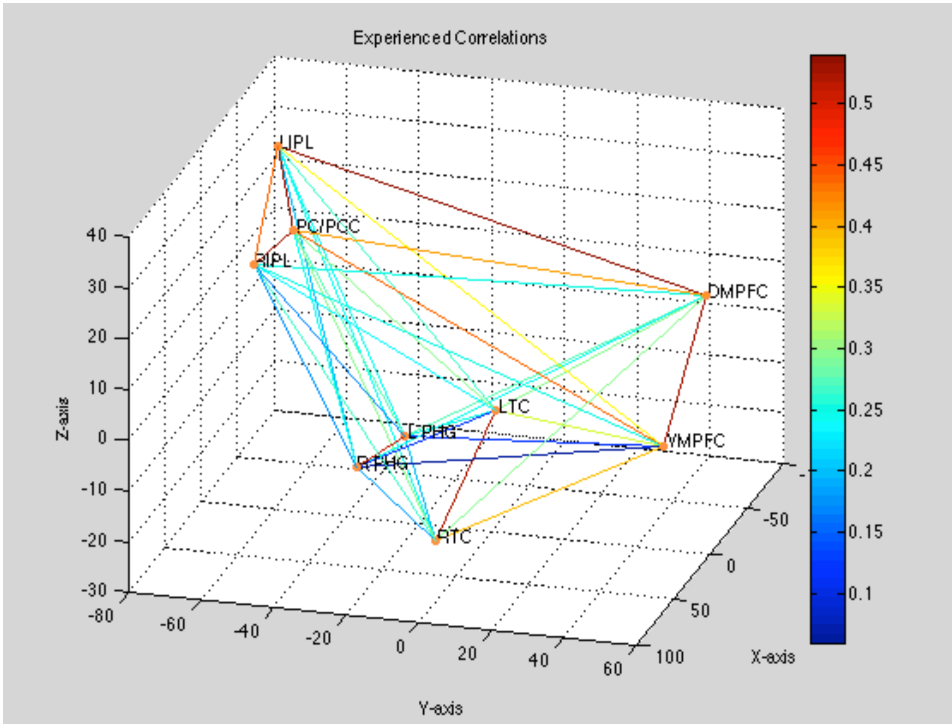


**Figure 1. Three-dimensional plot representing the weighted correlations between the brain regions for experienced meditators.**

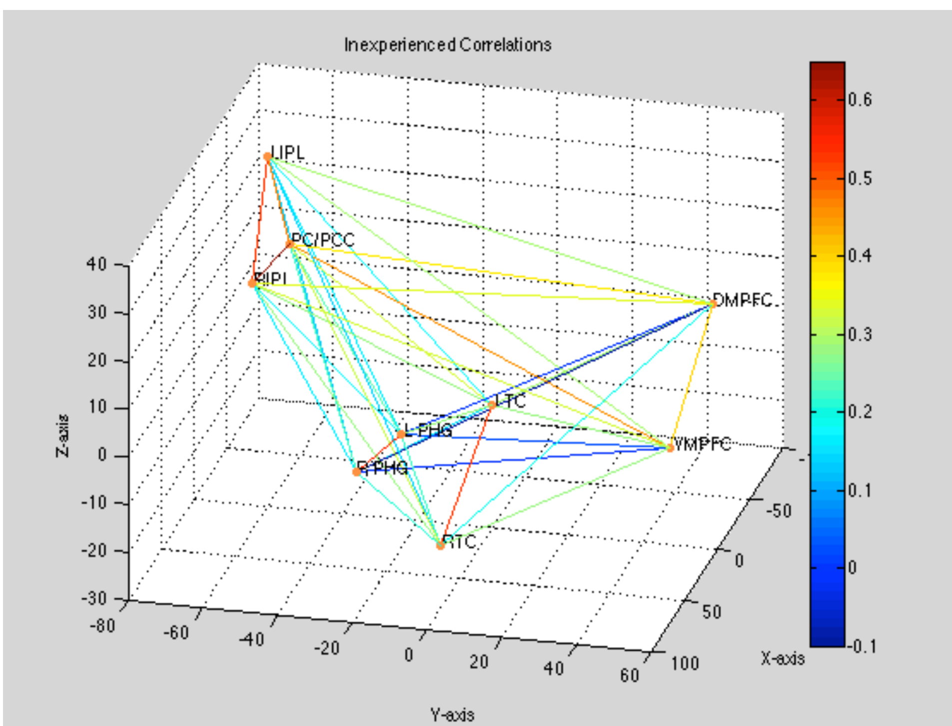


**Figure 2. Three-dimensional plot representing the weighted correlations between the brain regions for inexperienced meditators.**

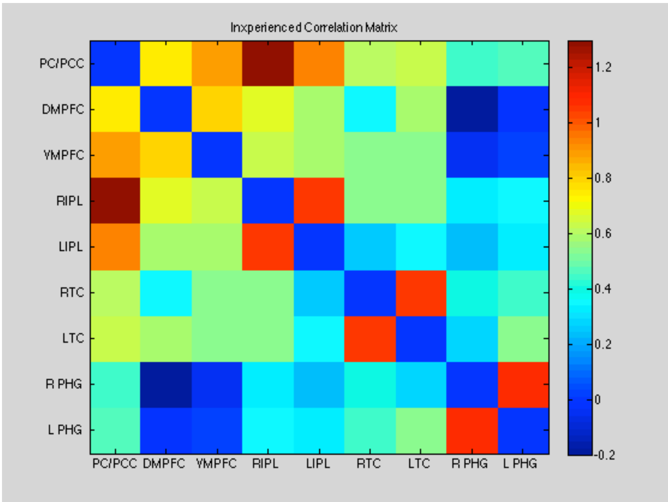


**Figure 3. Correlation matrix for inexperienced meditators**

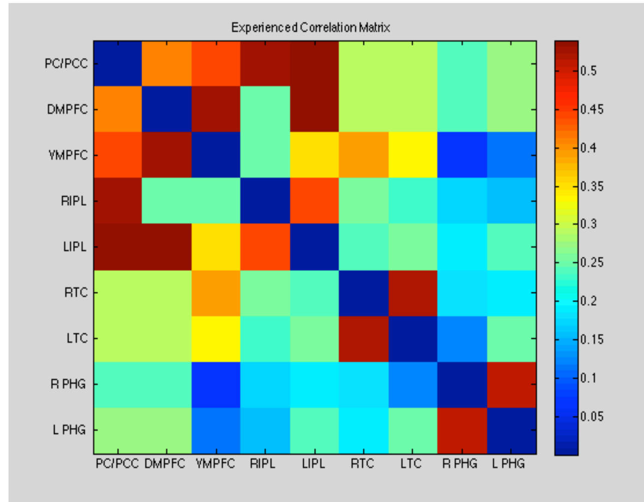


**Figure 4. Correlation matrix for experienced meditators**

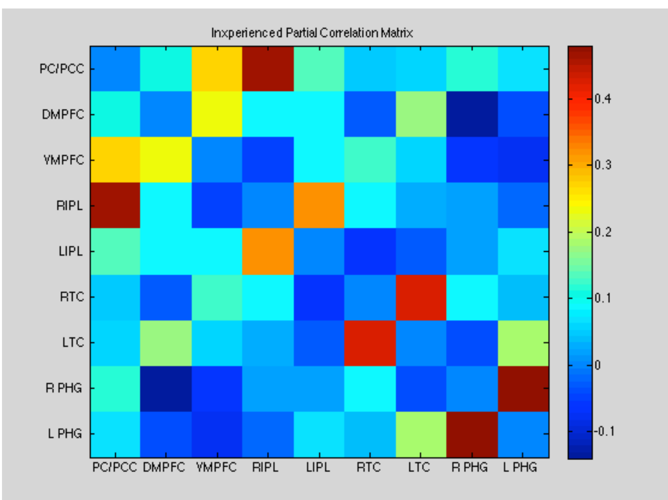


**Figure 6. Partial correlation matrix for inexperienced mediators**

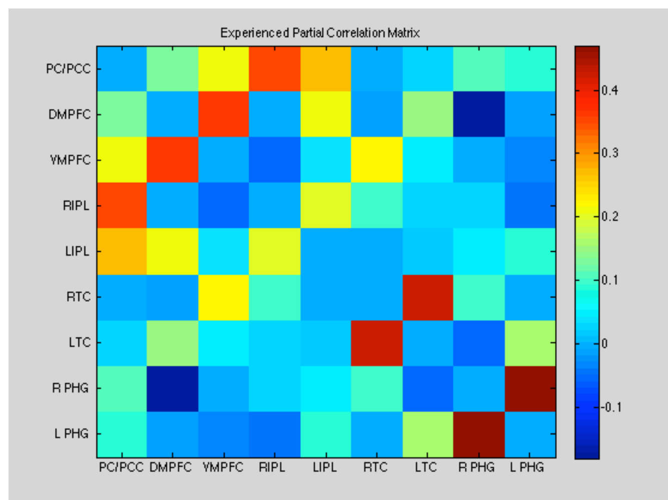


**Figure 7. Partial correlation matrix for experienced meditators**

**Table 4. Metric representing the amount of the total neural activity for experienced or inexperienced meditators from the correlation and partial correlation data.**

| Meditators | Total Original Neural Activity across Distance |
|---|---|
| Correlation Data | |
| Experienced | 11,190 |
| Inexperienced | 9,043 |
| Partial Correlation Data | |
| Experienced | 4,018 |
| Inexperienced | 3,465 |

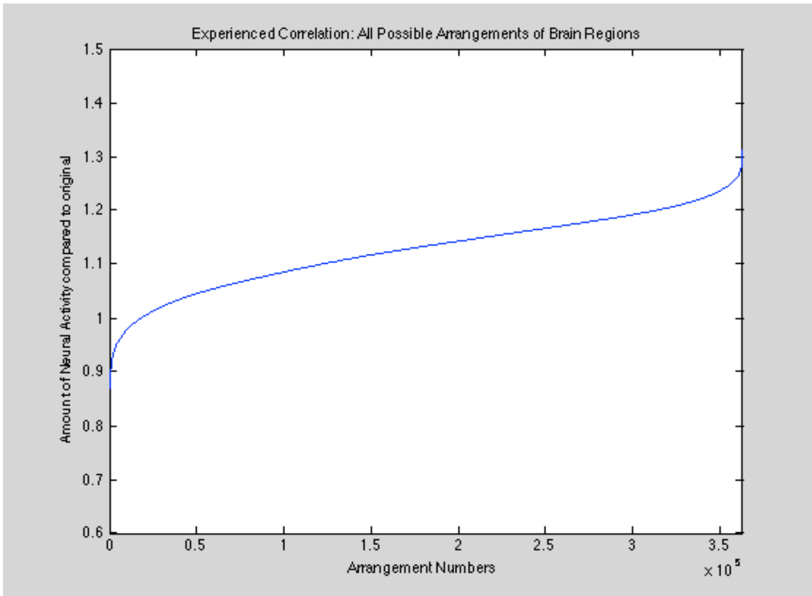


**Figure 5. Plot displaying the total neural activity across the distance between regions, when regions were randomly switched for all possible permutations for experienced meditators using the correlation data.**

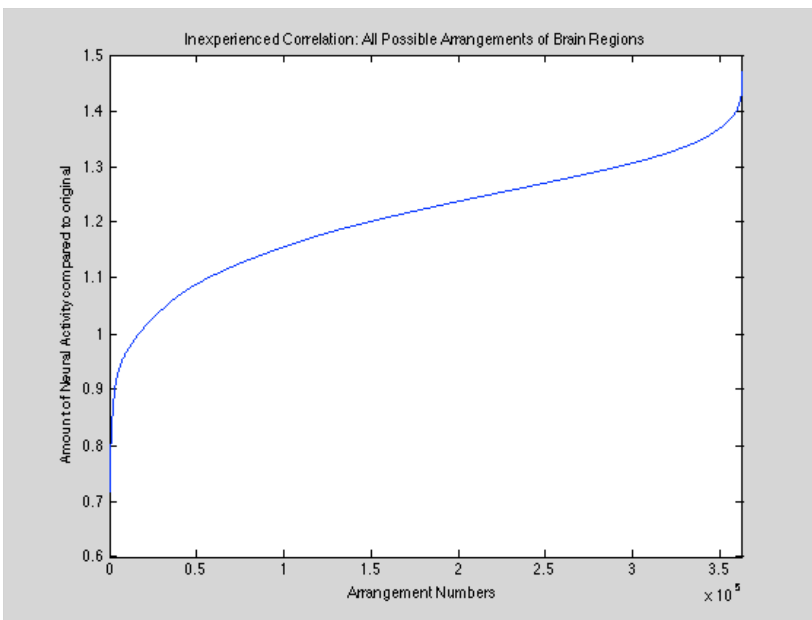


**Figure 6. Plot displaying the total neural activity across the distance between regions, when regions were randomly switched for all possible permutations for inexperienced meditators using the correlation data.**

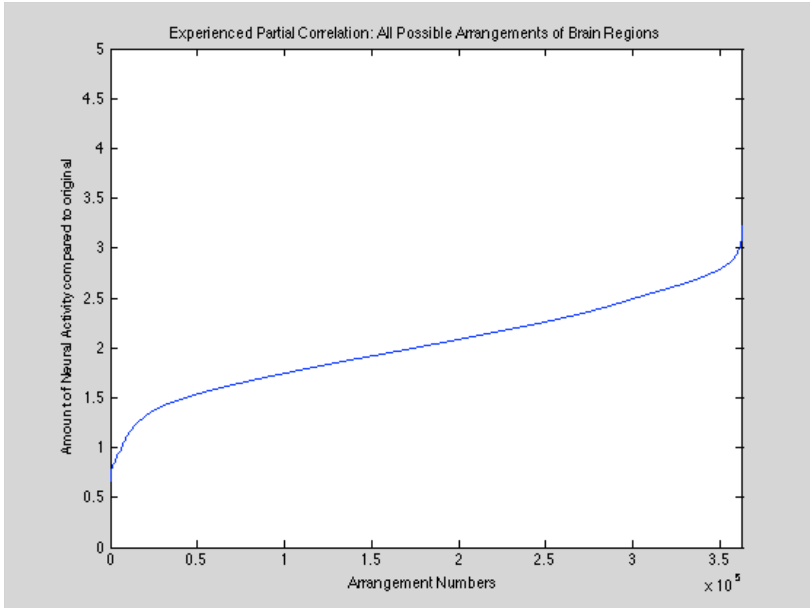


**Figure 7. Plot displaying the total neural activity across the distance between regions, when regions were randomly switched for all possible permutations for experienced meditators using the partial correlation data.**

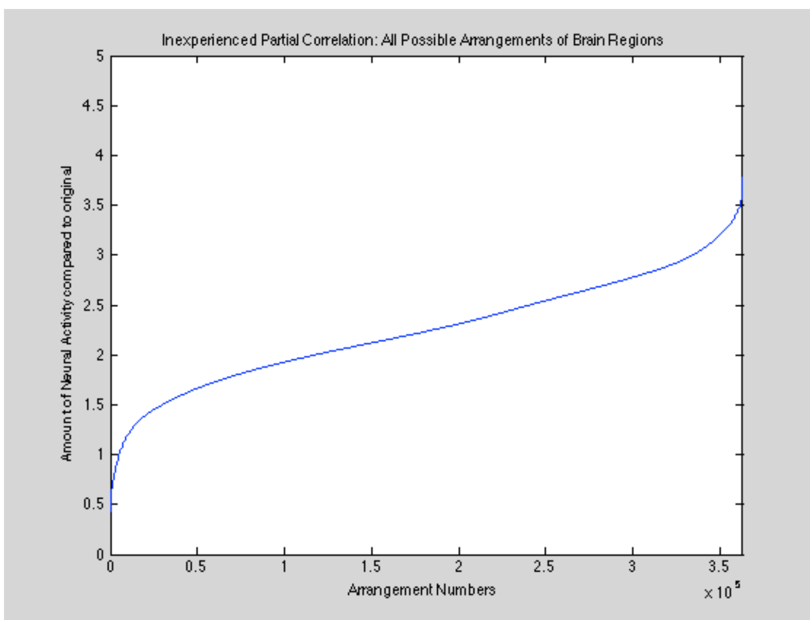


**Figure 8. Plot displaying the total neural activity across the distance between regions, when regions were randomly switched for all possible permutations for inexperienced meditators using the partial correlation data.**

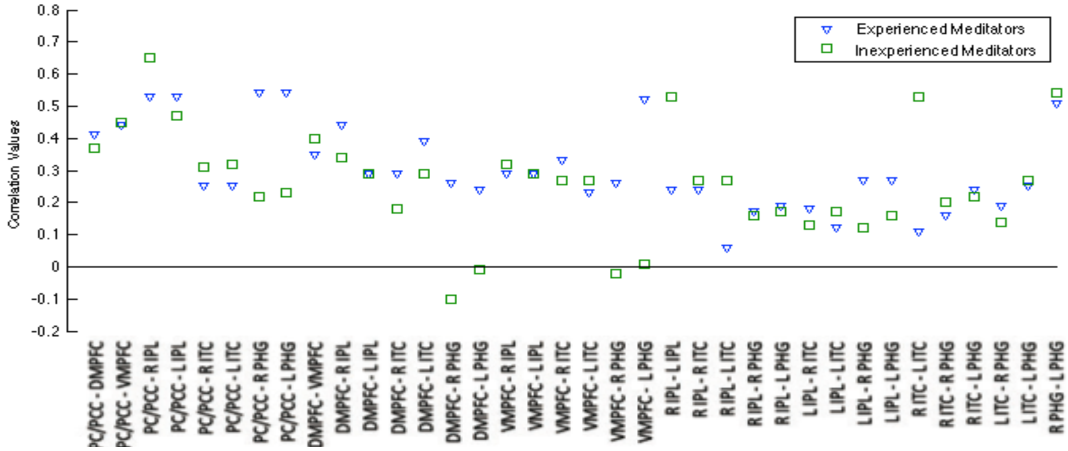


**Figure 9. Correlation values (y-axis) for all pairwise relationships between default network regions (x-axis). Blue triangles represent values for experienced meditators, and orange squares represent values for beginner meditators. PCC=posterior cingulate cortex; PC=precuneus; DMPFC=dorso-medial prefrontal cortex; VMPFC = ventro-medial prefrontal cortex; IPL= inferior parietal lobule; ITC= inferolateral temporal cortex; PHG= parahippocampal gyrus; R= right; L= left.**

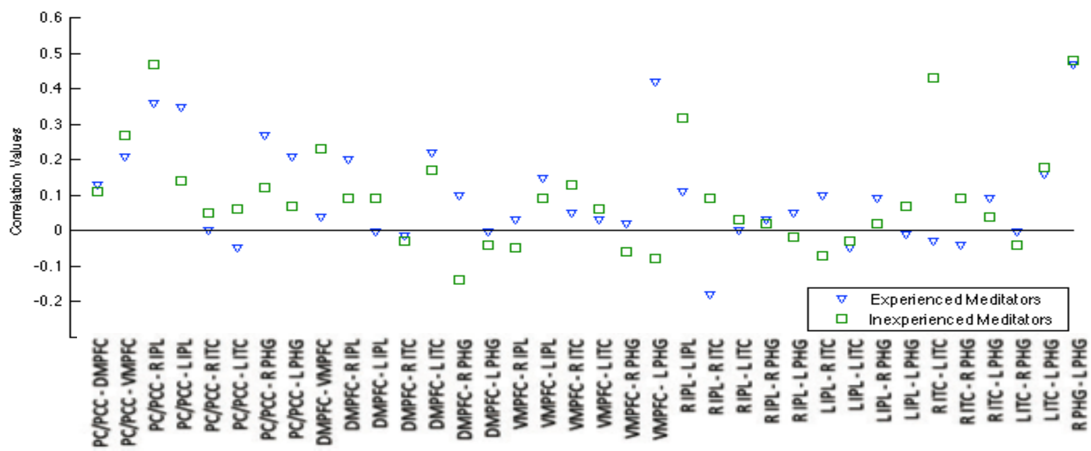


**Figure 10. Partial correlation values (y-axis) for all pairwise relationships between default network regions (x-axis). Blue triangles represent values for experienced meditators, and orange squares represent values for beginner meditators. PCC=posterior cingulate cortex; PC=precuneus; DMPFC=dorso-medial prefrontal cortex; VMPFC = ventro-medial prefrontal cortex; IPL= inferior parietal lobule; ITC= inferolateral temporal cortex; PHG= parahippocampal gyrus; R= right; L= left.**

Froelinger Results

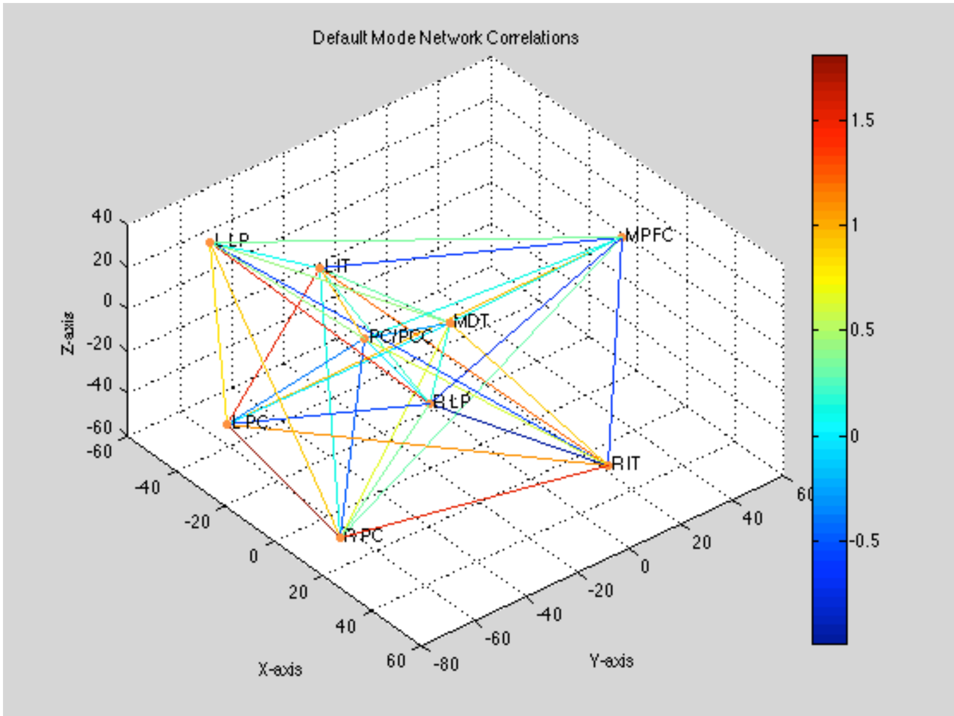


**Figure 11. Three-dimensional plot representing the weighted correlations between experienced meditators and the control**

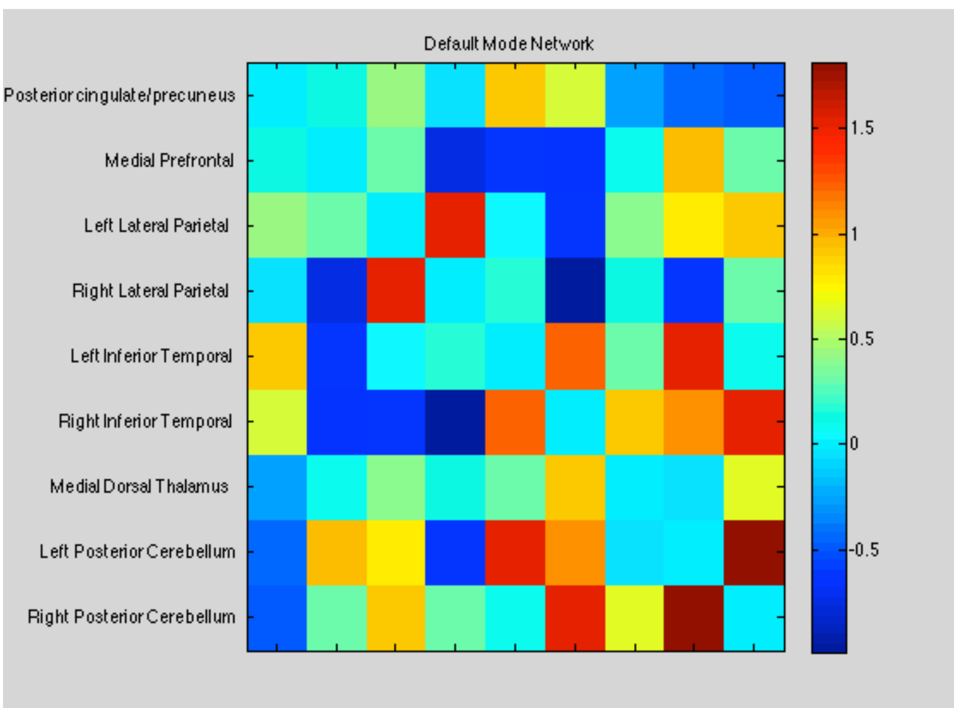


**Figure 12. Correlation matrix for the Default Mode Network**

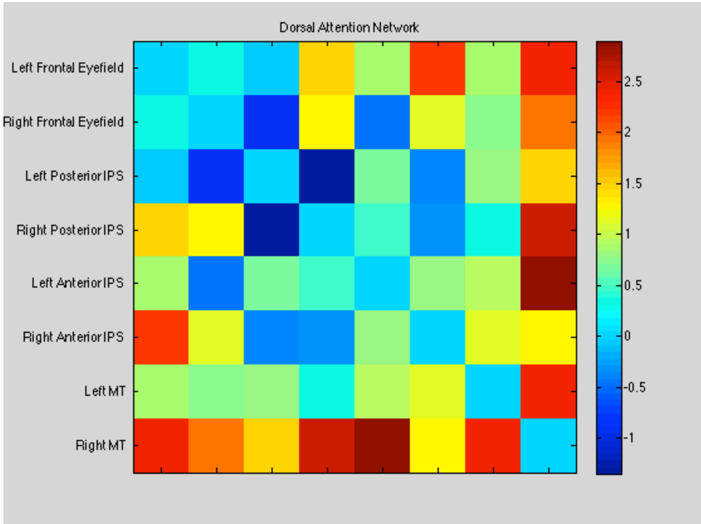


Figure 13. Correlation matrix for the Dorsal Attention Network

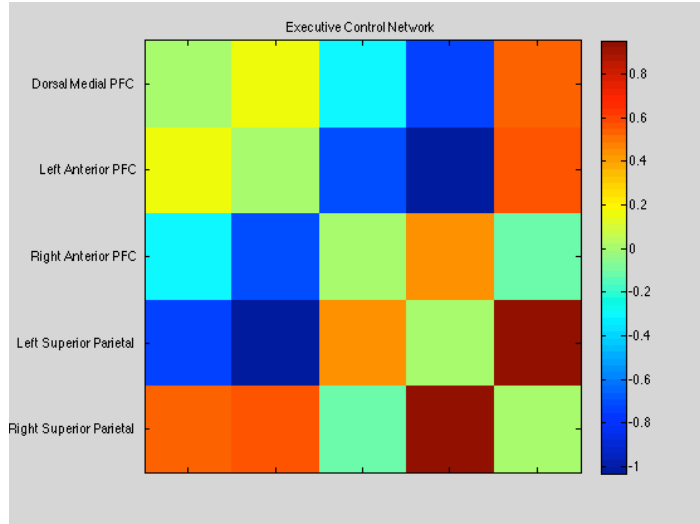


Figure 16. Correlation matrix for the Executive Control Network

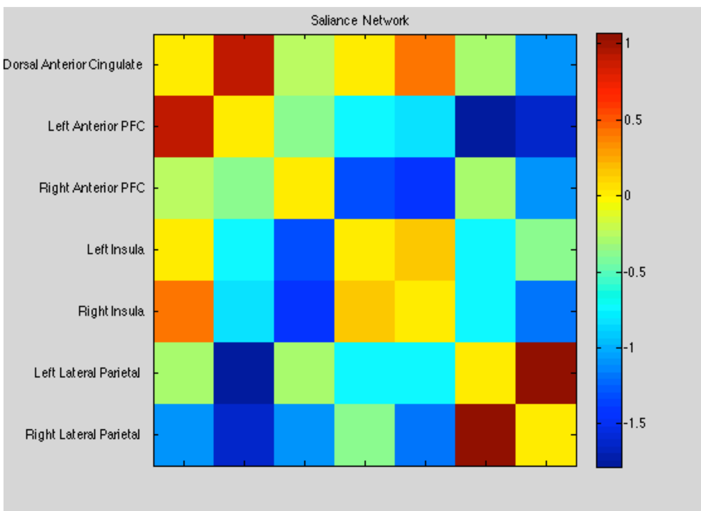


Figure 17. Correlation matrix for the Saliance Network

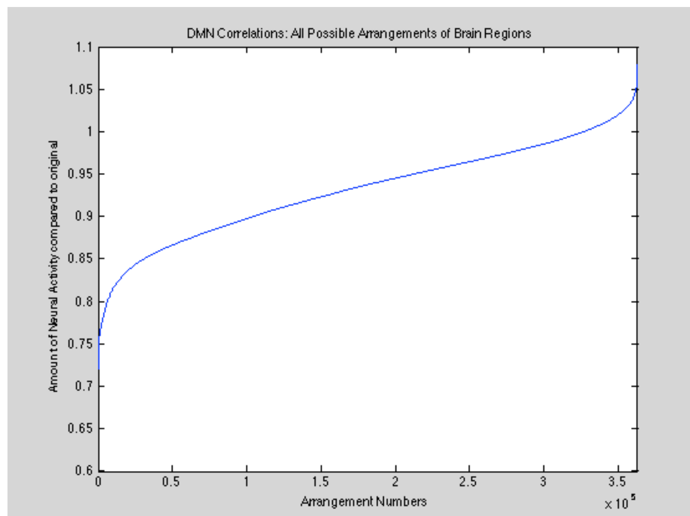


Figure 18. Plot displaying the total neural activity across the distance between regions, when regions were randomly switched for the DMN correlations between experienced meditators and the control.

Table 6. Metric representing the amount of the total neural activity for the DMN.

| | **Total Original Axonal Volume** |
|---|---|
| **DMN between Groups** | 11,378 |

**Discussion**

The three-dimensional plots representing the weighted correlations and locations made it very convenient to visualize the data. Figures 1 and 2 clearly show the increases and decreases in activity between brain regions in meditators versus non-meditators from the Taylor data, while Figure 13 show the correlation between meditators and non-meditators from Froelinger. Likewise, Figures 3-7 and Figure 14 also provide visualization of the correlation matrices, but without locations for the Default Mode Network of the Taylor and Froelinger data. These figures allow for one to better visualize and thus better understand the data. For example, one can clearly see the increased connectivity between the DMPFC and the right IPL in experienced meditators while comparing Figures 1 and 2. This increase could very well reflect the positive effects of mindfulness in terms of emotional resources and conscious awareness of the present moment.[14] This is supported by evidence that mindfulness is associated with increased mood and well-being, enhanced attention and cognitive performance, as well as reduced stress, depressive symptoms, anger and cortisol levels.[18-20]

As seen in Table 4, the metric representing the activity in the amount of neural activity across the distance between regions for unperturbed areas (it can also be seen from simply summing all of the correlations) shows that the experienced meditators displayed more overall activity in the DMN than the inexperienced, for both the correlation and partial correlation data. This does not agree with other findings that have shown that meditation causes an overall decrease in connections between regions in the DMN.[21] One explanation for this result is that these data only represent several regions of the DMN, and do not represent the entire network.

Once the total neural activity between regions, when regions were randomly switched for all possible permutations, were calculated they were sorted and then graphed as seen in Figures 7-10 for the Taylor data and Figure 18 for the Froelinger data. Surprisingly, the plots for experienced and inexperienced correlations appear to be very similar in the Taylor data. However, it can be seen in the results from the Taylor data that more of the random arrangements of brain regions for the experienced meditators appear to be closer to the activity of the original locations than inexperienced meditators, for both the correlation data and the partial correlation data. The results from the Taylor data show that most random arrangements cause an increase in activity and thus support the hypothesis that the location of brain regions, when compared to rearrangement with one another, creates one of the lesser amounts of activity in the DMN. Although the amount of activity did not vary as much as expected in the correlation data, the partial correlation data revealed a much larger increase in possible activity when regions were rearranged. However, the results from the Froelinger data showed that most random arrangements cause a decrease in activity and actually reject the proposed hypothesis. This discrepancy could be attributed to the fact that both data sets did not use the same brain regions within the DMN. Therefore, the results of the neural activity would depend on which brain regions are analyzed and would not be representative of the DMN as a whole. One possible future direction could be to perform the same analysis on data from other regions found to be active in the DMN, between experienced meditators and non-meditators and compare the results. It would also be interesting to analyze other brain regions involved in other networks, such as those shown in Figures 15-17 from the Froelinger data.

The limitations of this project are that some assumptions and generalizations were made. It was assumed that function could be measured by the amount of neural activity between regions and was directly proportional to the three-dimensional Euclidean distance between region centers multiplied by their pairwise correlation values and summed together. Upon comparing Figures 11 and 12 with the same plots by Taylor, it was found that the figures do not match. The Taylor figures show several inconsistencies in the pairwise relationship and do not correspond with the data shown in the table. This could be due to a misprint of the data or a mistake with the Figure. Regardless, it was assumed that the Figure was incorrect and that the data was correct.

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