INTRODUCTION

Having a healthy nervous system is a state of health most people take for granted, however approximately 12,000 new cases of paralysis occur in the United States each year. Most medical research has attempted to fix damaged nervous systems to allow the paralyzed to move again. Brain Computer Interfaces, or BCIs, attempt to fix the same problem by circumventing the damaged nervous system by utilizing the brain to control prosthetic devices replacing paralyzed limbs.

In order to progress BCI technology to be successfully used in the clinic, both engineering and scientific knowledge must be improved. The Neuron Preferred Direction Clustering project focuses on scientific knowledge about neuron populations and their firing patterns during reaching tasks in rhesus monkeys controlling a cursor on a screen. In 1986, it was established that neurons fire at varying frequencies according to direction of arm movement and that each neuron has a preferred direction in which it fires most frequently, and that these preferred directions distribute uniformly around all directions. Much of the literature does not focus on neuron preferred directions, but some have shown that their data indicate preferred directions that cluster to the same direction during brain control. These results do not conclude which reaching task scenarios produce the clustered results and why they occur, so there is a knowledge gap. Furthermore, it is speculated that clustered preferred directions would be detrimental to predictive success because little distinction among neurons can be made.

Brain control through a BCI is accomplished through a predictive mathematical algorithm. The algorithm can be of several types, one of which is a Kalman Filter (KF). The KF commonly utilizes different combinations of data to make movement predictions, including velocity (vKF), position-velocity (pvKF), and position-velocity-acceleration (pvaKF). Analyzing potential clustering patterns among these brain control KFs and hand control data will allow scientific knowledge to progress and help improve BCI technology.

OBJECTIVE

The objective of the Neuron Preferred Direction Clustering project is to further scientific understanding by determining if and when preferred direction clustering of a population of neurons occurs and to quantitatively determine the extent of that clustering. The situations to be evaluated for neuron preferred direction clustering involve a center-out reaching task completed by either brain control or hand control. For the brain control tasks, different brain control algorithms are to be evaluated, including a vKF, a pvKF, and a pvaKF. The results of these tests will determine when and how much preferred direction clustering occurs and does not occur among the different scenarios. These results will lead to a better understanding of how the brain and neurons function within different situations. The results may ultimately help provide a better understanding of how BCIs function.

HYPOTHESIS

The hypothesis of the project was that neurons would have more clustered preferred directions while performing brain control tasks with the three KF algorithms than neurons performing the same task with hand control. To quantify this hypothesis, the degree of clustering parameter is calculated from the circular variance of the neuron population’s preferred directions. Degree of clustering is unitless and ranges from 0 (uniform) to 1 (clustered). The hypothesis will be supported if the degrees of clustering of the brain control algorithms are significantly larger than the degree of clustering during hand control, as tested by paired t-tests.

METHODS

Other researchers in the SMILE lab completed all of the experiments that were analyzed in this project. All experiments were center out reaching tasks performed by two different rhesus monkeys controlling a cursor on the center of a screen by moving it to one of eight lit up targets. The cursor movement was either accomplished by hand or brain control. Brain control was done using one of three algorithms to predict cursor movement: vKF, pvKF, and pvaKF. Monkey 1 had data for all brain control algorithms and hand control, while Monkey 2 had data for vKF and hand control. Overall, the number of experiments per scenario was conducted from 4-18 times over 96-196 neurons in the population for 79-1290 trials each time.

The MATLAB code written for this project begins by loading processed neural data from the experiments and extracting the spiking times for each neuron for each trial. The firing times were restricted to 300-800ms into each trial in order to remove noise from the beginning of a movement and end it before the trial was complete. The remaining spike times were counted and the sum was assigned to one of the eight target locations. Each neuron’s preferred direction over all trials in an experiment was determined by fitting its firing rate towards each of the eight targets with a cosine fit, in which the direction the amplitude occurs at is its preferred direction. The equation of the cosine fit is shown in Equation 1.

\[ FR = (FR_{max}/2) \cdot \cos(D - PD) + FR_{max}/2 \]

\[ FR = \text{Firing Rate}, \ D = \text{Direction}, \ PD = \text{Preferred Direction} \]

For each experiment, circular variance was calculated from the vector containing all of the neuron’s preferred directions. Circular variance was used instead of variance because circular data cannot be analyzed normally as it repeats itself every 360 degrees. Circular variance was calculated with the CircStat MATLAB package. The circular variance parameter is unitless.
and varies from 0 (clustered) to 1 (uniform). The degree of clustering parameter is simply the circular variance subtracted from 1. Therefore, the data with a higher degree of clustering will be closer to 1 on the [0,1] scale than more uniformly disturbed preferred directions. Paired t-tests (5%) were used to determine statistical difference between the degrees of clustering.

RESULTS

For Monkey 1, in which the three brain control algorithms were analyzed along with hand control, the hypothesis was partly supported because the vKF brain control algorithm had a significantly larger (p < 0.05) degree of clustering than the hand control preferred directions. The results for both Monkey 1 and 2 can be found in Table 1.

<table>
<thead>
<tr>
<th>Monkey</th>
<th>Control Type</th>
<th>Deg of Clustering [0,1]</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>vKF Brain</td>
<td>0.46</td>
<td>0.05</td>
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<tr>
<td>1</td>
<td>pvKF Brain</td>
<td>0.27</td>
<td>0.16</td>
</tr>
<tr>
<td>1</td>
<td>pvaKF Brain</td>
<td>0.21</td>
<td>0.08</td>
</tr>
<tr>
<td>1</td>
<td>Hand</td>
<td>0.27</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>vKF Brain</td>
<td>0.65</td>
<td>0.14</td>
</tr>
<tr>
<td>2</td>
<td>Hand</td>
<td>0.34</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 1. The degree of clustering results for all brain control algorithms and hand control experiments analyzed are displayed along with their standard deviations. Both Monkeys 1 and 2 are shown with their respective types of control.

The other two brain control algorithms, pvKF and pvaKF, opposed the hypothesis, as they had comparable (p > 0.05) degrees of clustering to hand control, and they had significantly lower degrees of clustering (p < 0.05) than the vKF algorithm. This means that the vKF neuron preferred directions were relatively clustered together, while the pvKF, pvaKF, and hand control preferred directions were relatively uniform in distribution. The results can be seen in Figure 1. The same support for the hypothesis was found in the analysis of Monkey 2, in which only the vKF brain control algorithm was compared to hand control. The vKF algorithm showed significantly larger degree of clustering (p < 0.05) than the hand control circular variance. The results can be seen in Figure 2.

DISCUSSION

The results of the MATLAB analyses met the objective and suggested partial support of the hypothesis. For both monkeys, the vKF brain control algorithm had a significantly higher degree of preferred direction clustering than hand control. However, the hypothesis was not supported with the comparison of pvKF and pvaKF brain control algorithms to hand control for Monkey 1, as their degrees of clustering were not different than one another and were significantly more uniformly distributed than vKF preferred directions.

One limitation that may have led to this finding is that the pvKF and pvaKF brain control experiments did not restrain the arms of Monkey 1, while the vKF experiment had restrained arms. It is possible that the proprioceptive feedback mechanism inherent in arm movement is responsible for driving uniformly distributed preferred directions according arm movement directions. The other possibility is that adding the position term into the brain control algorithms drives the uniformity.

![Figure 1](image1.png)  
**Figure 1.** The overall degrees of clustering and standard deviations (red error bars) for all experiments for all types of brain control algorithms and hand control for Monkey 1. The vKF algorithm was significantly more clustered (p < 0.05) than the other two algorithms and hand control. The others were not significantly different from one another (p > 0.05).

![Figure 2](image2.png)  
**Figure 2.** The overall degree of clustering and standard deviations (red error bars) for all experiments for vKF brain control and hand control for Monkey 2 are shown. The vKF algorithm was significantly more clustered (p < 0.05) than hand control data, mirroring the results from Monkey 1.

The first is more likely, as the pvKF and pvaKF algorithms had similar results to hand control. This finding suggests an experiment to specifically alternate between different brain control algorithms and hand control both with arms restrained and unrestrained in order to observe clustering patterns among all possible scenarios. An additional parameter to test in this experiment is the success of each trial, so task success can be correlated to degree of clustering. Results from this experiment could lead to a better scientific understanding of how neural populations function according to arm movement availability and ultimately help improve BCI technology to aid its use in the clinic for paralyzed patients.

ACKNOWLEDGMENTS

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REFERENCES