Analysis The Effects of Grasp Dimension and Grasp Force on The Motor Cortex Neurons' Responses During Reach to Grasp in The Monkey

Negin EsmaeilZadeh[a], Samin Beheshti Zavareh[a], Fatemeh Salehin[a]

[a]Student, EE Department, Sharif University of Technology

This manuscript was compiled on February 1, 2022

A fundamental question is how the motor cortex is affected by motor activities and whether different motor activities in terms of dimension and force may lead to different effects on neurons. Several previous studies have shown that the motor cortex area is the origin of motor activities, which suggests this region's neurons firing to be significantly affected by motor stimulations. A pre-extracted set of electrophysiological data is processed and used for verification of the cited hypotheses, in this study. The data set is extracted from a macaque monkey's motor cortex area during a reach to grasp task and contains 161 trials(1). During a trial, the monkey had to grasp the object using either a side grip (SG) or a precision grip (PG). The monkey had to pull the object towards him in either a high or low pulling force way (HF and LF, respectively). As a result, from the possible combinations of grip types and object loads, the monkey had to perform in total four different trial types (SG-LF, SG-HF, PG-LF, PG-HF). The grip and force instructions for the requested trial type were provided to the monkeys independently through two consecutive visual cues (CUE and GO) which were separated by a one-second delay. The statistic tests on different neurons' responses to the switch release (SR-ON) suggest that the M1 area neurons' firing rate to be strongly influenced by the action start time and action period. Also, the statistical comparison indicates differences in neurons' responses between HF and LF grasp and between SG and PG grasp.

Motor Cortex | Monkey | M1 | Reach to Grasp | Dimension | Force | Neurons | Raster Plot | PSTH | Fano Factor | ISI

Ⅰn primates, the primary motor cortex (M1) (Brodmann area 4) is the major contributor to the corticospinal tract, the major descending pathway influencing skilled hand movements, and damage to these structures by stroke or spinal injury has devastating consequences for all those functions that depend on control of the hand (2). When reaching to grasp an object, human and nonhuman primates characteristically preshape the hand to match object properties, such as size and shape (3). Several motor cortical areas, including the dorsal premotor cortex (PMd) and primary motor cortex (M1), are involved in reach to grasp. The way the brain binds elementary movements together into meaningful action has been a topic of much interest and this encourages us to study the way different motor events are coded in the motor cortex (4).

In reaching tasks, the relationships between neuronal activity in the motor cortex and movement parameters have been widely debated, and remain controversial (5). It has been suggested that the neuronal activity in the primary motor cortex (M1) encodes such movement parameters as direction (6), hand position (7), velocity (8), acceleration (99), and reaching distance (10). However, other studies have argued that neural activity in the motor cortex correlates with kinetic variables, such as forces and torques (1111). In 1982, Georgopoulos et al. demonstrated for the first time a correlation between neuronal activity in the motor cortex and the direction of reaching movement (6) They showed that the average firing rate of M1 neurons during reaching movements varied with the direction of movement, and that each M1 neuron had a preferred direction (PD) for which its average firing rate was maximal.

Since then, directional tuning has been ubiquitously considered as a key property of neural activity in the motor cortex. However, the way these movement parameters affect neurons' firing is still less studied.

In this paper, we considered several neurons' activities of a monkey's motor cortex to discuss more on which events mostly affect the neurons firing and how this effect is indicated. We also studied whether different dimensions or force leads to different effects on neurons' firing. As the considered neurons are in motor regions we expect to see the most effects from motor events. However, it is still unclear whether this impact is due to the activity intention time or the time interval during a motor activity, thus we made two hypotheses to check these issues. Details of the methods and results will be discussed further.

Significance Statement

Most of our daily activities involve motor activities, so any disturbance or impairment in the function of neurons related to the motor cortex of the brain can disrupt many of our daily activities. Therefore, it is very important to know about the brain's motor cortex well and to understand the effect of the neurons in this area in performing various motor activities and vice versa. In this paper, the effect of different stimuli on motor neurons and the effect of motion dimension and pulling amount of force, which indicates how movement parameters are coded in these neurons are investigated by examining the experiments performed on a monkey in a reach to grasp task.

Author contributions

[1]All contributed equally to this work

The increase in the number of spikes after SR-ON, as we can see in Fig 1, and the increase in the average amount of firing rates, as we can see in Fig 2, for each neuron suggests that the SR-ON or somewhat GO-ON event may have an intensive effect on neurons firing rate. Regarding to this, two hypotheses are made:

First, the SR-ON and GO-ON events mostly affect the neuron's firings.

Second, only the GO-ON events mostly affect the neuron's firings.

The results of the p-value for the first hypothesis which is equal to 0 calculated with the permutation method and 1.6178×10^{-249} calculated with the t-test method suggest that our first hypothesis is almost true (p-value < 0.05).

Also, the results of the p-value for the second hypothesis which is equal to 0.0150 calculated with the permutation method and 2.4370×10^{-30} calculated with the t-test method suggest that our second hypothesis is almost true (p-value < 0.05).

As our first hypothesis is better satisfied, we cannot deny the impact of any of both SR-ON and GO-ON events.

The neurons inter spike intervals (ISI) seems to be almost fit an exponential distribution, which leads to the Poisson distribution of the spike trains. However, as we take a more careful look, we can find out an essential difference which occurs around Time Interval $= 0$ (Fig 3). As we can see despite an exponential curve, for a neuron the probability to have consequent spikes sooner than the refractory period ending time is almost zero. Thus, although an exponential
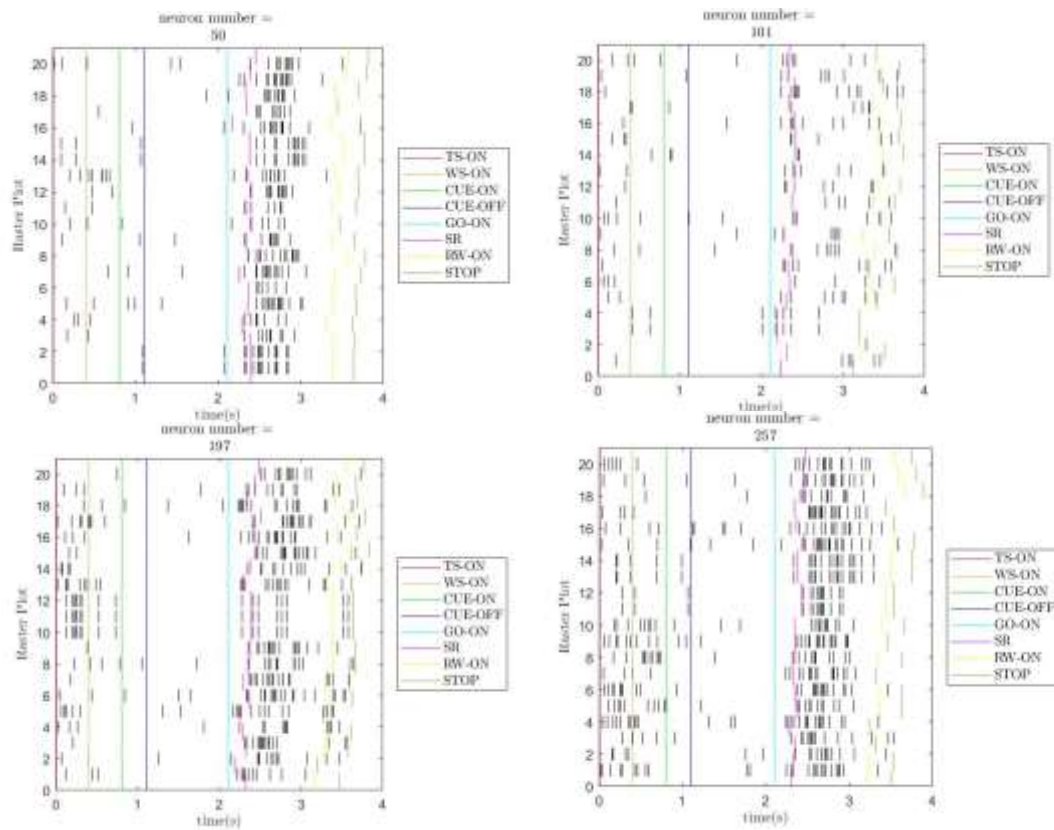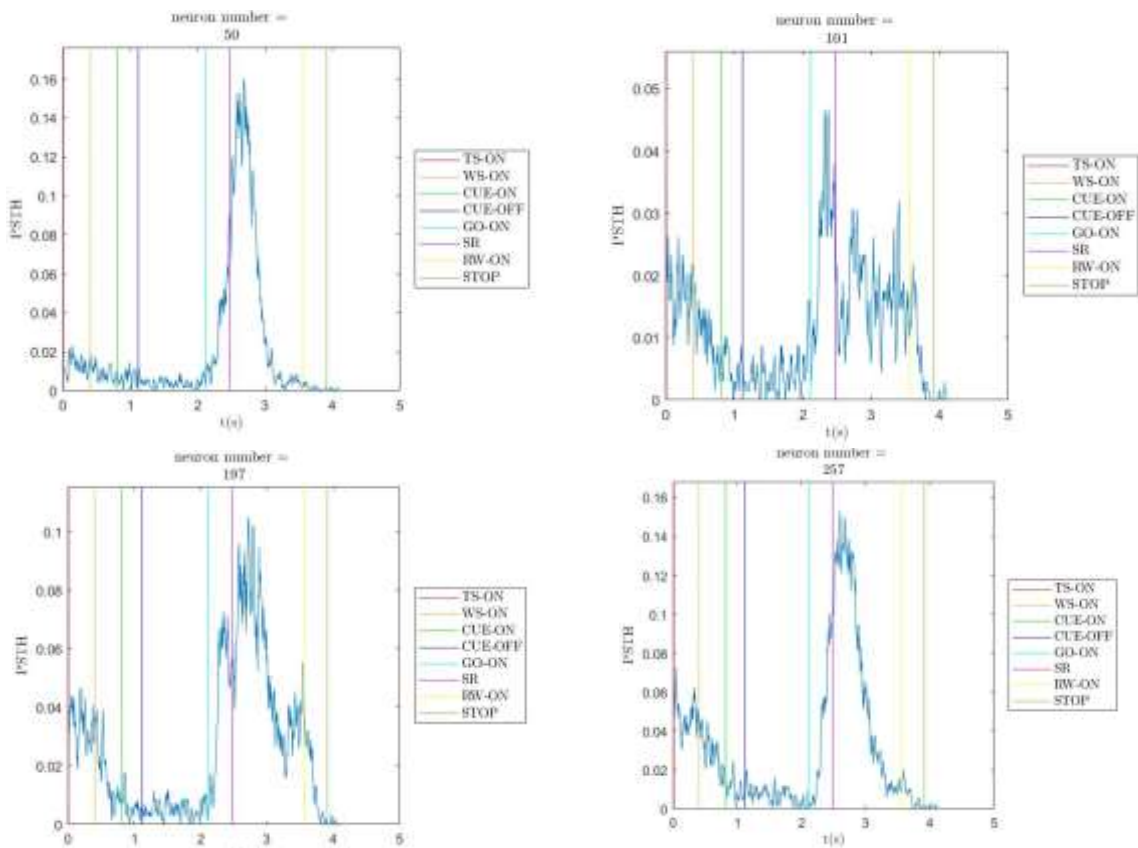
Fig 1. Raster plot of four selected neurons

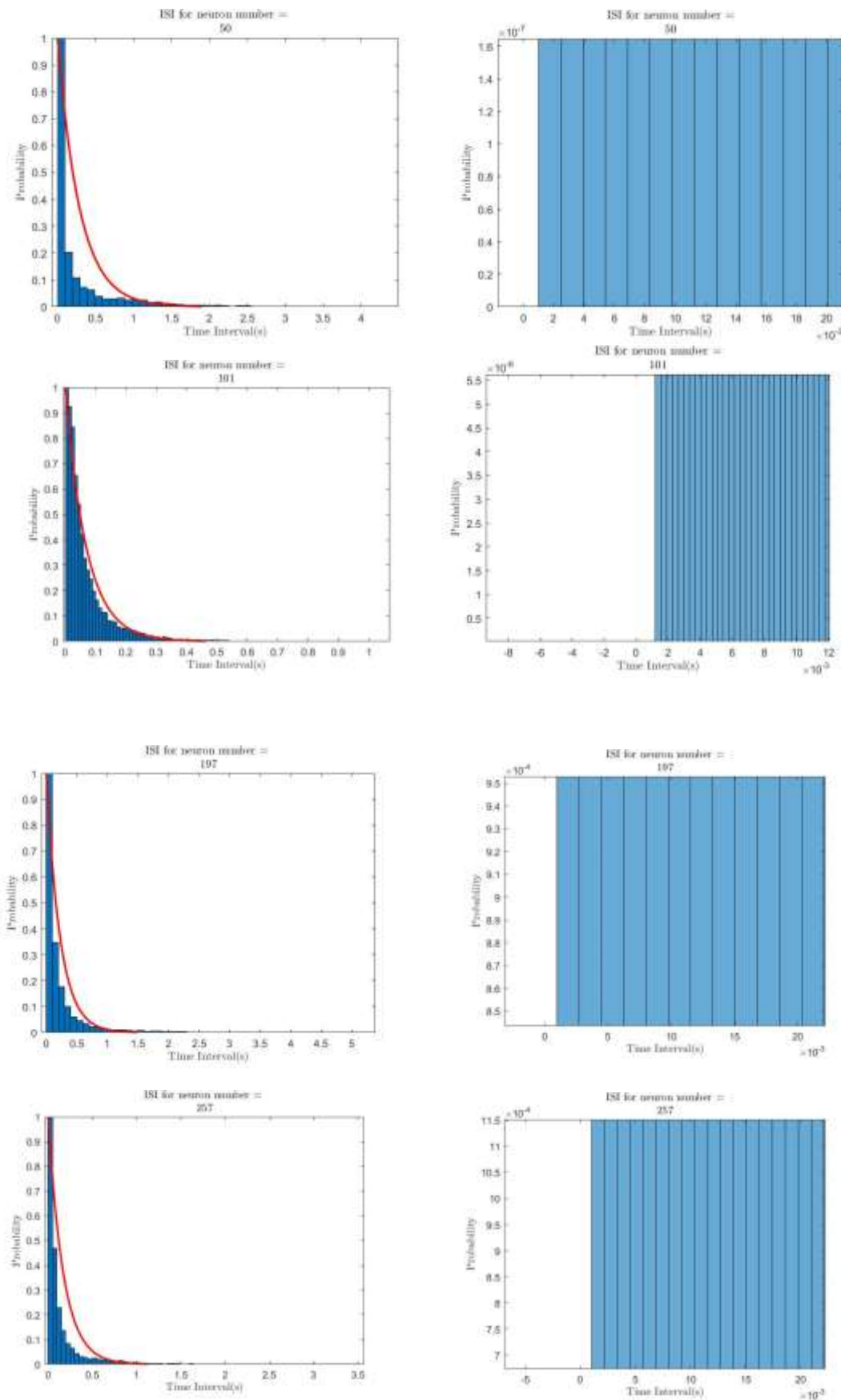

Fig 2. PSTH of four selected neurons

Fig 3. ISI of four selected neurons. The left and right distributions are the same. The left images are zoomed in around the zero time interval for better diagnosis of the probabilities of very small intervals.

curve fits our distribution the most, it is not suitable to use and so we do not have a well-formed distribution which fits our spike train data to be able to compare and analyze the effects of events with the statistical properties of this method.

The distribution of the Fano Factors for all trials of all neurons before and after the SR-ON event is also plotted to see the effect of the SR-ON on the regularity of spike trains. Although we expected to see a significant reduction in Fano Factors after SR-ON (as the neurons would fire at the maximum rate, limited by their refractory period times), no significant variation was detected from this test before and after SR-ON as we can see in the Fig 4.

For each neuron the PSTH graphs of the 4 different trial types are shown in a subplot (Fig 5). Differences can be seen between PG and SG trials and LF and HF trials. For several neurons, PG trials seem to cause a higher value of maximum average firing rate while resulting to a longer neuron response time of a neuron to the stimuli than SG trials and also HF trials seem to result to a longer neuron response time.

This is while we can also find neurons which showed no differences to different types of trials and also some rare once which showed totally inversed results. This may suggests that different neurons (depending on their location on the cortex) may have different sensitivities to grasp force and dimension.
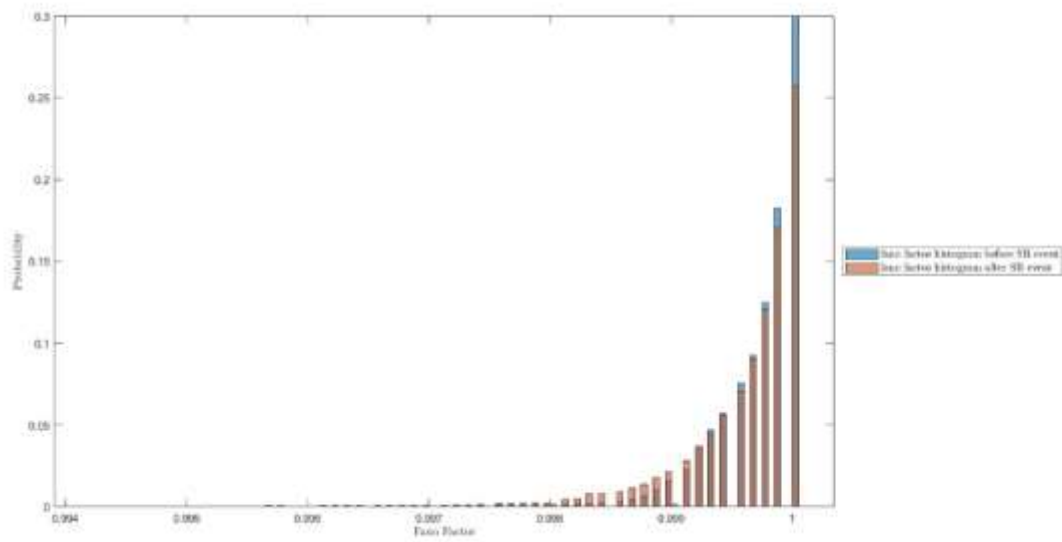
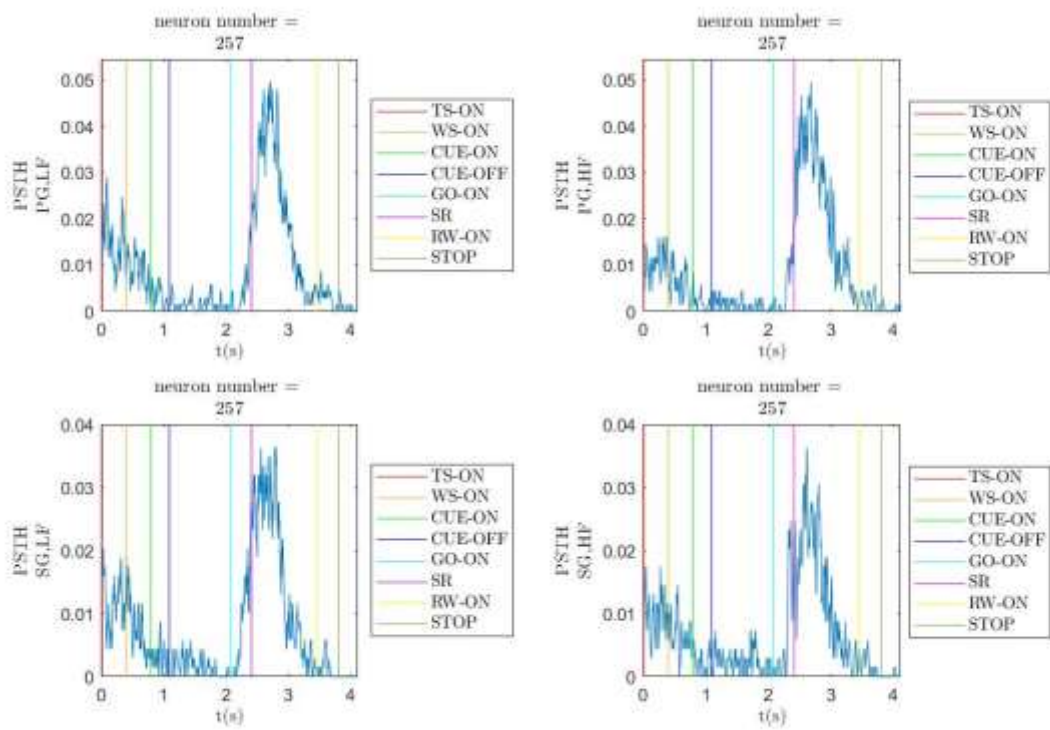*Fig 4. Distribution of Fano Factor before and after SR-ON event*

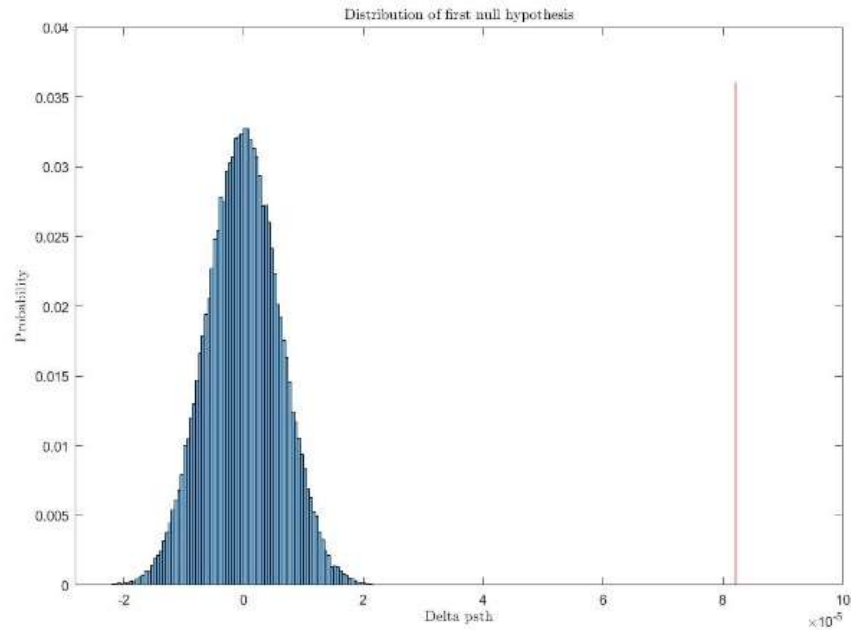
Fig 5. Different trial types PSTH of a selected neuron.

Fig 6. Distribution of the first null hypothesis is shown in this figure. The area under the curve after the occured sample (x = 8.21×10^{-5}) indicates our mis rate which is equal to the p-value of the first alternate hypothesis which is seemed to be very small. As we see in this nonparametric reached histogram we do not have any values more extreme than the sample value, this means the p-value here is equally zero.
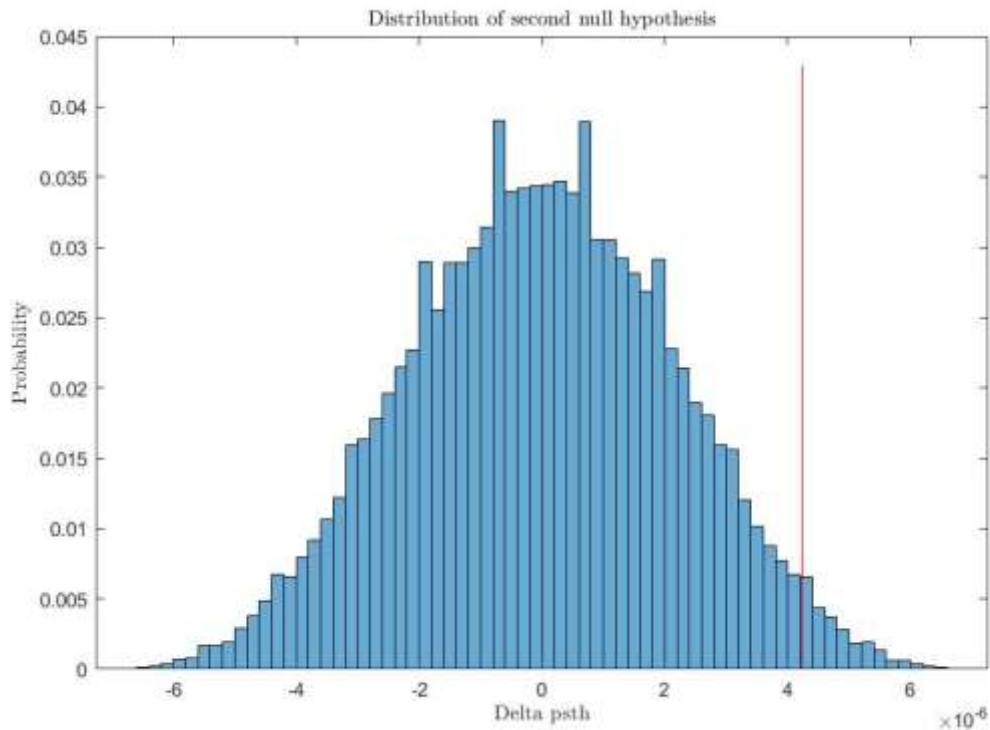

Fig 7. Distribution of the second null hypothesis is shown in this figure. The area under the curve after the red line indicates our mis rate which is equal to the p-value of the second alternate hypothesis which is seemed to be very small.

Discussion

The relation between the time, dimension type and force amount of SR-ON events (switch release activity) and M1 motor neurons firing rate was investigated as the main result of this study. Increase in almost all neurons' firing rate was observed after the SR-ON event, which was expected due to the fact that the examined neuron are from the brains motor area and they should be sensitive to motor activities. Differences between neurons responses to PG and SG grasps and between neurons responses HF and LF grasps were also detected. It seems that PG grasps lead to a sooner neuron firing occurrence and HF grasps lead to a sooner neuron firing occurrence too.

Similar to the previous studies this study also confirms the relationship between motor neurons firing rate and motor events (12, 13, 14) In this study despite the previous studies we tried to examine the accuracy of the hypothesis statistically and more accurately. In order to continue and complete the previous studies, in this study, in addition to investigating the effect of motor activity on the behavior of the motor neurons, we investigated the effect of differences on the responses of neurons in different simple activities (more precisely, the difference between how to encode 4 types of motion mentioned before).

The results of this study can be a suitable guide for further studies on the relation between motor activities and motor neurons firing, which can be also lead to the discovering of the motor neurons movement parameters encoding method. Future studies can focus on founding the exact differences between neurons responses to different movement parameters. Further detailed studies in this field can be helpful to better understand how motor information is processed in motor neurons and consequently to find treatments of possible defects.

Materials and Methods

In 2018 Thomas Brochier et al. published high-dimensional and multi-scale datasets that contain recordings from the motor cortex with a 10-by-10 Utah electrode array during controlled reach-to-grasp movements for two monkeys (L and N). They provide the activities of a large number of simultaneously recorded single neurons (93 and 156, for L and N respectively) along with the continuous neuronal "raw" signals (sampled at 30 kHz, and broadly band-pass filtered to 0.3 Hz–7.5 kHz) (1). In this paper, we used one of the recordings of this monkey's data (N monkey) to process and study our hypotheses.

The whole data contains 161 trails for each neuron (271 neurons). However, the trials which encountered errors during the extraction process and their recordings were incomplete or erroneously loaded were removed so that the further processes could be performed on error-free data. During a trial, the monkey had to grasp the object using either a side grip (SG) or a precision grip (PG). The monkey had to pull the object towards him in either a high or low pulling force way (HF and LF, respectively). As a result, from the possible combinations of grip types and object loads, the monkey had to perform in total four different trial types (SG-LF, SG-HF, PG-LF, PG-HF). To study the effects of grasp, grasp dimension, and grasp force on neurons' responses we went through several steps. In the first step, different processing methods were used to see each

neuron's response to various trial events (new trial sequence (TS-ON), monkey preparation time (WS-ON), trial choosing type (CUE-ON), CUE-ON ending time (CUE-OFF), trial force type (GO-ON), switch release time (SR-ON), reward time (RW-ON), trial ending time (WS-OFF)).

Regarded to this, we plotted each neuron's PSTH graph and RASTER plot. The RASTER plot graph is plotted with each trial event times mentioned, to see what is each event's effect on the neurons' spike rates (1). For better visualization, as the trials were too many to show, for each neuron we chose 20 random trials to show the raster plots. For the PSTH graph, we took the average of all trials' estimated neuron firing rates using a rectangular window (moving average method), thus for each neuron, we plotted a PSTH which is a good estimation for neurons' average firing rates through trail times.

We also attempt to find which point process fits motor neurons spike trains, thus we plotted the ISI (Inter spike interval) distribution of each neuron. Furthermore, knowing a neuron's ISI distribution helps us to discover whether or not a neuron is firing at its nearly most firing rate. As it was mentioned previously in the results, from these observations we made two hypotheses:

First, the SR-ON and GO-ON events mostly affect the neuron's firings.

Second, only the GO-ON events mostly affect the neuron's firings.

For evaluating each of these two hypotheses we went through two methods.

In order to test the first hypothesis, in the first method, we made a reduced spike train by separating the spike trains of each trial from one second before and one second after the

SR-ON event, which also includes the GO-ON event time, and took the average of each neuron's peri-stimulus time histogram (PSTH) of the reduced spike train. These steps were also performed for the second hypothesis too, with the only difference that for the second hypothesis we made the reduced spike train by separating the spike trains of each trial from only 50ms before and after the GO-ON event time, as we wanted to avoid the SR-ON event's effects to come over.

To prove each hypothesis we made the null hypothesis and tried to check the probability of the values more extreme than the occurred-sample provided that the null hypothesis was correct and in this way calculated the P-Value. As we do not have the distribution of the samples, we used the permutation method, which is a nonparametric method by generating 10000 samples, on our statistical population (all samples of the reduced PSTH results mentioned before) to evaluate the P-Value of the hypothesis.

For the second method, we examined the amount of Fano Factor before and after the related event (SR-ON) time. This idea is based on the fact that if an event causes a neuron to fire consecutively, the neuron will approximately fire at the maximum rate (limited by the refractory period time during which a neuron can not fire) and this will lead to more regular neuronal spikes. Also, according to the Fano Factor definition, a neuron's spikes are more regular as the Fano Factor gets closer to zero.

$$Fano\ Factor = \frac{Var[N(t)]}{E[N(t)]}$$

In order to compare the effects of different grasp dimensions, and grasp force on neurons' responses we separated the trails in terms of the trail types (SG-LF, SG-HF, PG-LF, PG-HF) for each neuron and tried to compare the peri-stimulus time histogram (PSTH) for different trial types of each neuron.

References

1. Thomas Brochier, Lyuba Zehl, Yaoyao Hao et al. Massively parallel recordings in macaque motor cortex during an instructed delayed reach-to-grasp task

2. Lawrence and Kuypers, 1968; Dum and Strick, 1991; Porter and Lemon, 1993

3. Castiello et al. 1993, 1998; Jeannerod 1984; Mason et al. 2004; Paulignan et al. 1991; Roy et al. 2002; Santello and Soechting 1998; Wing et al. 1986

4. Machiko Ohbayashi 2021; The Roles of the Cortical Motor Areas in Sequential Movements

5. Graziano MS, Aflalo TN. Mapping behavioral repertoire onto the cortex. Neuron. 2007

6. Georgopoulos AP, Kalaska JF, Caminiti R, Massey JT. On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. The Journal of Neuroscience. 1982

7. Georgopoulos A, Caminiti R, Kalaska J. Static spatial effects in motor cortex and area 5: quantitative relations in a two-dimensional space. Experimental Brain Research. 1984

8. Moran DW, Schwartz AB. Motor cortical representation of speed and direction during reaching. Journal of Neurophysiology. 1999

9. Flament D, Hore J. Relations of motor cortex neural discharge to kinematics of passive and active elbow movements in the monkey. Journal of neurophysiology. 1988

10. Fu Q, Flament D, Coltz J, Ebner T. Temporal encoding of movement kinematics in the discharge of primate primary motor and premotor neurons. Journal of Neurophysiology. 1995

11. Sergio LE, Kalaska JF. Changes in the temporal pattern of primary motor cortex activity in a directional isometric force versus limb movement task. Journal of Neurophysiology. 1998

12. Carlos E. Vargas-Irwin et al. 2010; Decoding Complete Reach and Grasp Actions from Local Primary Motor Cortex Populations

13. Mukta Vaidya et al. 2015; Neural coordination during reach-to-grasp

14. Marsha M. Quallo et al. 2012; The Activity of Primary Motor Cortex Corticospinal Neurons during Tool Use by Macaque Monkeys