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Preparatory Activity in PMd Neurons to Bypass a Virtual Obstacle in the Reaching Path

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Abstract**—***We recorded neural activities in dorsal premotor areas (PMd) when monkey was preparing to perform arm reaching movements in motor-set period before his actual execution. He was required to select one of four possible movements (reaching a target on the top-left or top-right corner of a virtual cube, moving straightly or making a detour) in accordance with two sets of instruction cues. Among the neurons recorded, we analyzed 118 neurons which showed set activities during movement preparation. More specifically, 46 neurons were modulated with respect to the obstacle-related conditions;42 neurons, with respect to target location and 15 were tuning to both. In trials in which the virtual obstacle appeared, successful trials were also compared to unsuccessful (hit-obstacle) trials, in which the monkey moved straight to the target instead of bypassing the virtual obstacle. The motor-set activity of a specific group of neurons was significantly different in set activities between successful and unsuccessful trials. Their activity was strongly modulated by the spatial position of the virtual obstacle, indicating that those cells likely participated in the planning of the hand path (straight or curved in counterclockwise direction) based on visual information about the virtual obstacle. At the same time, neurons in which the spike activity modulation with respect to the virtual obstacle position was relatively weak, did not show significant differentiation of the motor-set, preparatory activity between successful and unsuccessful trial types.*

INTRODUCTION

FOR purposeful and efficient performance of motor action, preparatory processes often follow the process of motor selection, before the actual execution of the desired movements. How cortical activities are correlated with target locations has been studied by a large number of researchers [1-4]. However, the target information alone is not sufficient. For example, in order to start the engine of a car, you need to insert the key into the key hole which is usually behind the steering wheel. We need to bypass the steering wheel to reach it. In this case, preparation of movement includes selection of reaching target and hand path. The objective of this study is to investigate how different types of hand paths with and without avoiding virtual obstacles are represented in the neural activity during movement preparation. It is well known that set-related activity is prominent in dorsal premotor areas (PMd) [5,6]. It has been reported that PMd neurons exhibited activities significantly tuned to arm use and target location [7, 8], direction and distance [9]. It is of interest to study the participation of this area in different aspects of motor preparation, which are different types of hand path (straight or curved in counterclockwise direction) and target location in our study. We analyzed neuronal activities in monkeys while they were performing a motor task in which the process of motor selection and the development of movement preparation were largely separated. In this report, we show that except target location, different type of intended hand path was also reflected in the preparatory activity in PMd neurons.

I. METHODS

One rhesus monkey (5.5 kg) was trained to perform a three-dimensional instructed-delay reaching task in a virtual reality environment. The Institutional Animal Care and Use Committee approved the behavioral paradigm, surgical procedures and general animal care.

Cortical activity was collected by a Multichannel Acquisition Processor and associated RASPUTIN neuronal recording suite (Plexon Inc.). A 5-channel multi-electrode manipulator "Mini Matrix" MM05 (Thomas RECORDING) and the quartz glass coated fiber electrodes (80 µm in diameter) with platinum/tungsten core (25 µm in diameter) were used in current study. Impedance of 1 - 5MOhm is well suited for single unit isolation. A recording chamber was designed to match the contour of monkey's skull with 23 mm (anterior-posterior) by 21 mm (medial-lateral) of recording space. Kinematics data was sent to the PC at 150 Hz from an Optotrak 3020 motion tracking system (Optotrak/3020, Northern Digital Inc.).

Behavior task

The monkey was trained to perform a arm-reach task in virtual reality (VR) by following two sets of instructions with the 1st cue indicating the target location (top-left or top-right corner of a virtual cube) and the 2nd cue indicating whether a virtual obstacle existed. The existence of a virtual obstacle determined the type of hand path to follow in movement execution (straight or curved in counterclockwise direction) (Fig. 1). The task commenced when the center ball (green) with a virtual cube appeared on the screen after an intertribal interval (3 sec). The monkey was required to match it with a red ball, which corresponded to his wrist position, for 500-1,000 msec. Then another green ball representing the target will be shown on top-left or top-right corner of the virtual cube for 500 msec (1st cue). If the wrist position remained to match the center for 1,000 msec during the subsequent delay period, the 2nd instruction cue (500 msec) was given to complete the information for the subsequent action followed by a set period (1,000 – 1,500 msec). When a purple bar appeared on the screen during the 2nd cue, the monkey was required to move around and hit the target during movement execution. In the other condition (nothing was shown during the 2nd cue), the monkey was trained to

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move straight to the target. After the set period, both targets were shown on the screen as a GO signal, telling the subject to reach the target. The monkey was rewarded with juice after each successful trial. The target location was randomly presented during experiment. Obstacle conditions were switched between blocks, with each block containing five successful trials of either target

II. DATA ANALYSIS

Kinematic data analysis

In this study, the curvature of hand trajectories under "without obstacle" and "with obstacle" conditions were differentiated. For the purpose of quantifying the difference, the maximum deviation of the path from a straight line drawn between endpoints divided by the length of that straight line was measured for each single trial. For each target condition and obstacle condition, the linearity ratio was averaged across all trials. Statistical analysis showed that the linearity ratio was significantly different in two obstacle conditions (t-test, $p<0.05$). The obstacle condition was switched between blocks. To prevent the monkey from copying the previous movement without focusing on the instruction cues, the length of one trial was set to about 3.5 ~ 4.5 sec plus 3 sec inter-trial interval (ITI). To confirm that, we also compared the successful rate of the 1st trial after obstacle condition was switched with the successful rate of the rest trials. Their distributions were not significantly different ($p>0.05$, χ^2 test).

Cortical data analysis

We classified a neuron as "task-related" if its distribution of discharge rates (spikes per second) in five task periods (1st cue and delay, 2nd cue, set and movement) was significant in at least one of four types of movements(two targets and two types of hand path) compared to control period (center hit to target on) (t-test, $p<0.05$). The duration between onset of the 2nd cue and GO signal is 1,000 ~ 1,500 msec (uniformly distributed). For the set period, a time window of 1,000 msec starting at the onset of the 2nd cue was used to determine whether the activity was modulated with the target location, virtual obstacle condition or both. To reveal the relationship to the target and virtual obstacle, a two-way ANOVA with two factors (target and virtual obstacle) was performed. Based on this analysis, we classified set-related neurons into three classes: *1)* modulated only to target; *2)* modulated only to virtual obstacle condition; *3)* modulated to both target and virtual obstacle condition.

To assess how much information about the target position and obstacle position were represented in neural activities; we calculated indices defined with the following equations

$$TgtIdx = \frac{(X_{R-OBS} + X_{R-NO}) - (X_{L-OBS} + X_{L-NO})}{(X_{R-OBS} + X_{R-NO} + X_{L-OBS} + X_{L-NO})} \tag{1}$$

$$ObsPosIdx = \frac{(X_{R-OBS} - X_{L-OBS})}{(X_{R-OBS} + X_{L-OBS})} \tag{2}$$

In the equation, $\boldsymbol{X}$ is the average discharge rate in the set-cue period over 1,000 msec time window, categorized with an appropriate subscript. Thus, X_{R-OBS} means the discharge rate during the set period before reaching to the right target in a clockwise direction. X_{L-NO} means the discharge rate during the set period before reaching straight to the left target. The value of indices range from -1 to +1. If "right target" is greater than "left target", the TgtIdx (target index) is positive and vice versa. If "right virtual obstacle" is greater than "left virtual obstacle", the ObsPosIdx (Obstacle position index) is positive and vice versa.

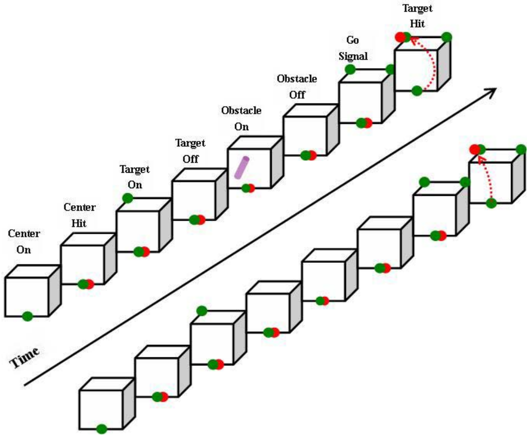

Fig. 1.Behavioral task. Temporal sequences of behavioral events. Center On: center ball was shown on the screen. Center Hit: the monkey matched the center ball with the red ball representing his wrist position. Target On: one of two targets was shown for 0.5 sec. Target Off: the target went off for 1 sec. Obstacle On: The purple bar representing the virtual obstacle was shown or nothing was displayed (0.5 sec). Obstacle Off: If virtual obstacle was shown in the 2nd cue, it went off for 1 – 1.5 sec. Go signal: the monkey was allowed to reach. Target Hit: If the monkey chose the correct hand path and hit the right target, a successful sound was played and he was rewarded with juice.

III. RESULTS

We observed task-related activity in 346 PMd neurons, 118 of which showed set activity. In this report, we focus on neuronal activity in the set period. By applying two-way ANOVA on these 118 PMd neurons, 46 were classified as modulating only to virtual obstacle cues (see METHODS) (Table 1). An example is shown in Fig 2A. The shading rectangle marks the time window of 1,000 msec in the analysis (aligned to the onset of the 2nd cue). On the other hand, 42 were classified as modulating only to target (Fig 2B) and 15 were classified as modulating to both target cue and virtual obstacle cue. Figure 2C shows an example of a PMd neuron in this category.

Active responses in obstacle condition may due to visual information processing and/or movement trajectory preparation. Therefore we compared neural activities

TABLE I
MODULATION OF PMD NEURONS TO TARGET AND VIRTUAL OBSTACLE

n	Virtual obstacle only	Target only	Target and virtual obstacle	others
118	46(38)	42(35)	15(13)	15(13)

The table shows the number of neurons in each category; percentages are in parentheses.

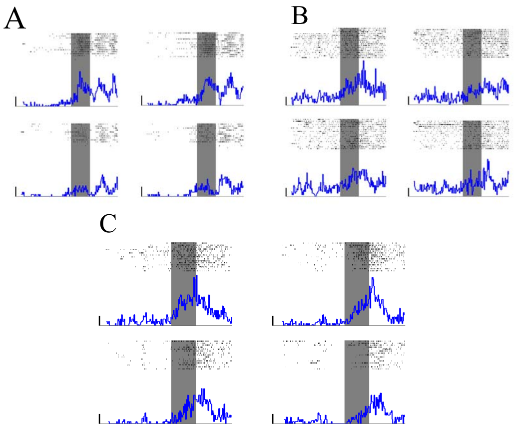

Fig 2. Three examples of neuronal activity. A): In the raster displays, each row represents a trials and each dot shows when the cell discharged. The highlight area marks the 1,000 msec time window in the set period starting at the onset of the 2nd cue (virtual obstacle). The vertical bar in each panel represents 10 spikes/sec. Below each raster display, peri-event histogram aligned to the onset of the 2nd cue (30 msec bin) are drawn. Target conditions are separated in columns and two obstacle conditions are shown in rows (top row: with obstacle; bottom row: no obstacle). The neuron was more active if the monkey prepared to reach left and right target with a more curved hand path, but was less active during preparation for straight movement. B): This neuron was active when the monkey was prepared to reach left target, regardless of the curvature of the intended hand path. C): This cell was active in the preparation for making a detour but less active when he prepared to move straight to the target. Besides, it also modulated with two target locations (lower discharge rate in preparation of moving to the right target).

between successful and unsuccessful trials with the same visual instructions. In the unsuccessful trials, monkey did not manage to avoid the virtual obstacle. In other words, when virtual obstacle was shown, the trajectories were either curved in counterclockwise direction without touching the virtual obstacle (successful) or almost straight to the target and hit the virtual obstacle (hit-obstacle). The average firing rates in the 1,000 msec time window of those two types of trials were arranged according to target location and compared by using t-test. Results show that 55 of 118 neurons have significantly different modulation in set period. One example is shown in Fig. 3A (the same neuron as Fig. 2A). The blue line represents successful trials to the left target with virtual obstacle. The red line represents trials in which monkey moved straight to the left target. The neuron was less active in set period if the monkey did not manage to avoid the virtual obstacle. On the other hand, 63 neurons did not show significant difference (Fig. 3B). The activity of this neuron in all successful trials was shown in Fig. 4. Interestedly, the cell shown in Fig. 3A modulated to virtual obstacle positions (t-test, $p<0.05$), while neuron in Fig. 3B did not show significant difference with respect to the spatial location of the obstacle (Fig 2A).

Subsequently, we performed quantitative analysis for groups of cells showing different activity between successful and unsuccessful trials. The distribution of the virtual obstacle position index (eq. (2)) was compared with the target index (eq. (1)) among neurons in PMd. The density histograms and cumulative distribution of the absolute obstacle position index is shown in left panels in Fig 5. The blue curve represented index from neurons which showed difference between successful trials and hit-obstacle trials. The red curve represented neurons which did not show the difference. To better compare density histograms between the two groups of neurons, negative values of one group were presented (in red). The distribution differed significantly between these two groups of cells (Kolmogorov-Smirnov test, $p<0.01$). It can be seen that cells having different activity in successful and hit-obstacle trials showed strong preference of the position of the virtual obstacle. The density histograms and cumulative distribution of the absolute target index were shown in right panels in Fig. 5. However, the distribution of target index did not show significant difference (Kolmogorov-Smirnov test, $p>0.05$).

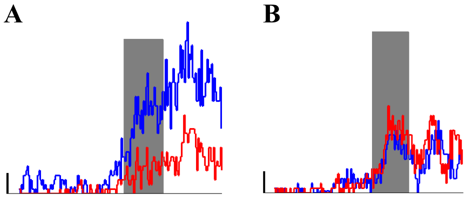

Fig. 3 Two examples of neural activity between successful trials with virtual obstacle and unsuccessful trials (hit-obstacle). The blue represents the successful trials to one target. The red represents hit-obstacle trials to the same target, in which the monkey did not manage to move around the virtual obstacle. A: This cell showed significant difference in discharge rate during set period in these two types of trials. B: This cell showed similar activity in the set

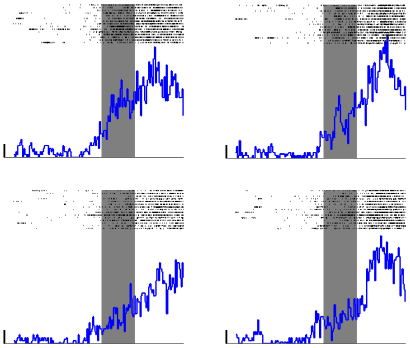

Fig. 4 The same cell as Fig. 3A. Two target conditions are represented in columns. Top row shows trials with virtual obstacle, while bottom row is no obstacle condition.

IV. DISCUSSION

In this study, we analyzed the set activity in PMd in an instructed delay task. The monkey was required to reach one of two targets following two types of hand path: straight or curved in counterclockwise direction given two sets of visual cues. About one third of neurons with set activity were modulated to target location. Another one third was tuned to obstacle condition. In order to investigate whether PMd neurons show differential activity during preparation for different type of hand path, we compared successful trials (with virtual obstacle) and hit-obstacle trials with the same target position. The two types of trials had the same instruction cues but different curvature of the actual movement. Therefore, neurons showing different discharge rates in set period may participate in planning different type of hand path. About one half of neurons with set activity did show the difference. The quantitative analysis showed that the set activity of this group of neurons was strongly modulated to the spatial position of the virtual obstacle. Not only was a visual image, the virtual obstacle was also processed as movement information. On the contrary, neurons showing similar discharge rates in successful and unsuccessful trials, have no or weak modulation of spatial position of the virtual obstacle (Fig. 2A and 3B). They might not be directly involved in hand-path planning.

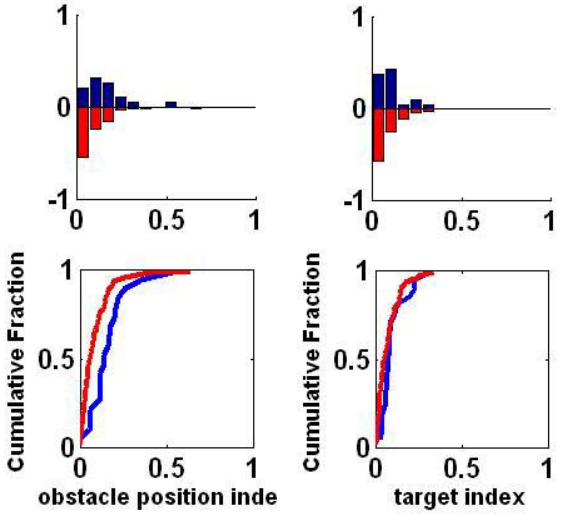

Fig. 5 Density histograms of indexes and Cumulative fraction. The blue represents neurons which showed significant different discharge rate during set period between successful trials with obstacle and unsuccessful trials (hit-obstacle). The red represents neurons which did not show the difference. The left panel shows the distribution of obstacle position index among the two groups of neurons. The right panel shows the distribution of target index among two groups of neurons.

Eye position was not controlled during present study, but the monkeys occasionally looked away from the stimuli, even before and during movements. These eye movements did not seem to affect cell activity. Previous reports on neuronal activity in PMd have argued against an effect of eye position on set- and movement-related activity or an effect of that activity on eye movements [10, 11]. In addition, the peak velocity in two different types of hand path did not show significant difference (t-test, p>0.05). However, the curvature and the overall distance traveled are not differentiated in this study. More experiments are required to further separate both effects on neural activities. For example, the spatial mapping between perceived and actual movement could be varied such that the overall trajectories for the same type of movement would be significantly different.

V. FUTURE WORK

It is well known that neurons make use of variations in spike rate and timing to transmit information. Current data analysis was only focusing on rate coding without considering temporal information. We would like to use temporal patterns to predict whether a given class of signal occurred on a single trial. From engineering perspective, it would be very useful for prosthetic control. The decoding algorithm combining with instantaneous movement control signals from other cortical areas could generate a more smooth and natural trajectory.

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