

# Motor Intention Activity in the Macaque's Lateral Intraparietal Area.

## II. Changes of Motor Plan

R. MARTYN BRACEWELL, PIETRO MAZZONI, SHABTAI BARASH, AND RICHARD A. ANDERSEN

*Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

### SUMMARY AND CONCLUSIONS

1. In the companion paper we reported that the predominant signal of the population of neurons in the lateral intraparietal area (area LIP) of the monkey's posterior parietal cortex (PPC) encode the next intended saccadic eye movement during the delay period of a memory-saccade task. This result predicts that, should the monkey change his intention of what the next saccade will be, LIP activity should change accordingly to reflect the new plan. We tested this prediction by training monkeys to change their saccadic plan on command and recording the activity of LIP neurons across plan changes.

2. We trained rhesus monkeys (*Macaca mulatta*) to maintain fixation on a light spot as long as this spot remained on. During this period we briefly presented one, two, or three peripheral visual stimuli in sequence, each followed by a delay (memory period, M). After the final delay the fixation spot was extinguished, and the monkey had to quickly make a saccade to the location of the last target to have appeared. The monkey could not predict which stimuli, nor how many, would appear on each trial. He thus had to plan a saccade to each stimulus as it appeared and change his saccade plan whenever a stimulus appeared at a different location.

3. We recorded the M period activity of 81 area LIP neurons (from 3 hemispheres of 2 monkeys) in this task. We predicted that, if a neuron's activity reflected the monkey's planned saccade, its activity should be high while the monkey planned a saccade in the neuron's motor field (MF), and low while the planned saccade was in the opposite direction. The activity of most of the neurons in our sample changed in accordance with our hypothesis as the monkey's planned saccade changed.

4. In one condition the monkey was instructed by visual stimuli to change his plan from a saccade in the neuron's preferred direction to a saccade planned in the opposite direction. In this condition activity decreased significantly ( $P < 0.05$ ) in 65 (80%) of 81 neurons tested. These neurons' activity changed to reflect the new saccade plan even though the cue for this change was not presented in their RF.

5. As a control we randomly interleaved, among trials requiring a plan change, trials in which the monkey had to formulate two consecutive plans to make a saccade in the neuron's preferred direction. The activity remained unchanged ( $P < 0.05$ ) in 22 of 31 neurons tested (79%), indicating that the neurons continued to encode the same saccade plan.

6. In a variant of the task, the cue to the location of the required saccade was either a light spot or a noise burst from a loudspeaker. Of 22 neurons tested in this task, 16 (73%) showed activity changes consistent with plan changes cued by visual or auditory stimuli.

7. Alterations in the monkey's intentions, even in the absence of overt behavior, are manifested in altered LIP activity. These activity changes could be induced whether visual or auditory cues were used to indicate the required plan changes. Most LIP neurons thus do not encode only the locations of visual stimuli, but also

the intention to direct gaze to specific locations, independently of whether a gaze shift actually occurs.

### INTRODUCTION

We continue in this paper our investigation of the role that neurons in the monkey's lateral intraparietal area (area LIP) play in the preparation of saccadic eye movements. Many neurons in this area of the posterior parietal cortex (PPC) are active from the moment a stimulus appears in their visual receptive field (RF) until a saccade to foveate that stimulus is completed (Gnadt and Andersen 1988). If a delay is imposed between stimulus presentation and saccade execution (memory saccade task) (Hikosaka and Wurtz 1983), these neurons show distinct stimulus-related and saccade-related (SR) discharges, as well as elevated activity during the delay ("memory"-period, or M, activity) (Barash et al. 1991a; Gnadt and Andersen 1988). M and SR responses are especially prominent in area LIP (Barash et al. 1991a,b), an area distinguished from other PPC areas by its strong connections with other saccade-related regions, such as the superior colliculus and frontal eye fields (Andersen et al. 1990a; Blatt et al. 1990; Lynch et al. 1985).

During the delay in a memory saccade task, the monkey receives no sensory input and makes no eye movement, but must remember where the stimulus has just appeared and plan an appropriate saccade to that location. We have been studying the M activity to see what role it plays in the sensorimotor transformations related to saccadic eye movements.

On the basis of double saccade and back saccade tasks (Barash et al. 1991b; Gnadt and Andersen 1988), we have demonstrated that LIP cells code in motor coordinates: they become active if a saccade is planned into their motor field (MF), even if no visual target ever falls within their RF. Moreover, these results and the results of the delayed double saccade experiments described in the accompanying study (Mazzoni et al. 1996a) indicate that the sustained (M) activity of a majority of LIP cells reflects the monkey's intention or motor plan to make the next saccade into its MF.

We reasoned that if this activity did indeed reflect the monkey's motor plan, then alterations of this plan, even in the absence of overt behavior, should be manifest in altered LIP activity. We report here the results of experiments using a "change of motor plan" (CP) paradigm designed to test this hypothesis. In this paradigm, one, two or three targets were presented sequentially during the fixation period. The monkey did not know how many, nor which, targets would

be presented, as the different trial types were pseudorandomly interleaved. He presumably planned to saccade to the first target when it appeared, and then changed his plan if a subsequent, different, target appeared. To ensure that the monkey planned to make the eye movement during the delay period and not after the fixation light was extinguished, he was required to saccade within a very short reaction time in order to receive a reward. We were thus able to correlate changes in the motor plan with alterations in single-unit activity in LIP. The results support our conjecture that neuronal activity in LIP reflects the monkey's intention to make the next saccade.

## METHODS

The methods we used in this experiment are the same as those of the companion paper (Mazzoni et al. 1996a), except for the behavioral tasks and data analysis. We describe these next.

### *Behavioral tasks*

Each monkey learned to perform several tasks involving saccades for the purposes of several studies. The ones used in this study are the visual memory saccade task, the visual change of plan task, and the visual-auditory change of plan task.

The *memory saccade* (MS) trial is described in the companion paper (Mazzoni et al. 1996a). Briefly, a peripheral visual stimulus was briefly presented in the monkey's visual field while he maintained gaze on a fixation spot straight ahead. After a delay, the fixation spot was turned off, which cued the monkey to make a saccade, in total darkness, to the remembered location where the peripheral stimulus had appeared. The peripheral stimulus was placed at an eccentricity of 5–25° along one of eight directions (the 4 cardinal and the 4 diagonal directions).

The responses of most LIP neurons during a MS trial consist of sensory response, a saccade-related response, and sustained activity during the delay between stimulus presentation and fixation spot offset (memory activity, M), or any combination of these (Barash et al. 1991a,b; Gnadt et al. 1988). These responses are maximal for stimuli in a circumscribed sensory response field (receptive field, RF), and for saccades in a neuron's MF. These responses are described in more detail in the companion paper (Mazzoni et al. 1996a). We used MS trials to locate each neuron's visual RF and saccadic MF.

If a neuron had sustained M activity we then tested it in the CP paradigm. The CP task consisted of up to eight classes of trials, all involving stimuli at one of two locations. Location A (the neuron's *preferred* location) was in the RF, whereas location B (the nonpreferred location) was outside the RF, diametrically opposed to location A (Fig. 1). In all classes the monkey had to maintain gaze on a fixation point (FP) while various combinations of stimuli appeared, and then, after FP offset, make a saccade to the remembered location of the last target to have appeared.

Figure 1 shows the time course of onset and offset of the FP and the visual stimuli in each of the eight classes. For most cells we used these time segments or a slight variation of them. The first two classes were standard memory saccade trials with the stimulus located at A (inside the RF, class 1) or B (outside the RF, class 2). Each trial began with the appearance of the FP, followed after 800 ms by the appearance of the visual stimulus (A or B), which stayed on for 300 ms. A delay of 400 ms (the memory, or M, period) followed the stimulus' offset. The FP was then extinguished and the monkey made a saccade, within 350 ms, to the remembered location of A or B.

Classes 3 and 4 required a change of motor plan. As in the first two classes, a stimulus (A in class 3, B in class 4) was presented

for 300 ms after the monkey had been fixating for 800 ms. After the 400-ms delay period (M1), however, a second stimulus (B in class 3, A in class 4) appeared for 300 ms, and was followed by a second 400-ms delay period (M2).

We pseudorandomly interleaved trials of all classes in the CP task. The monkey could not know in advance, therefore, how many nor which targets would appear in a given trial. Because he had only 350 ms to make the required saccade after FP offset, he had to always be ready to make a saccade to the most recent target's location in case the FP was turned off. He thus presumably planned a saccade to each stimulus as it appeared and maintained that plan throughout the M period that followed. When a second stimulus appeared as in classes 3 and 4, he then had to change his saccade plan and maintain the new one during the next M period.

Classes 5 and 6 were control trials. It is possible that the mere appearance of a second visual stimulus, independent of the saccade plan, might affect the activity of LIP neurons and thus confound any activity changes related to the change in saccade plan. We controlled for this possibility by presenting two stimuli, as in classes 3 and 4, but both at the same location (A in class 5 and B in class 6).

In classes 7 and 8 we presented three stimuli, requiring two changes of saccade plan. In class 7 the monkey had to first plan a saccade to A, then change that plan to a saccade to B, then change it again to a saccade to A. Class 8 had a B-A-B plan sequence.

The third task used in this study is the *visual-auditory change of plan* (CPVA) task. This is a variant of the CP task in which the stimulus could be either visual or auditory. We used this task to see whether any patterns of responses observed in the CP task might be specific to visual stimuli or could be elicited by nonvisual spatial cues. The visual stimulus was the same light spot used in the other tasks and was located at 8° eccentricity to the right or to the left of the fixation point. The auditory stimulus was a 20- to 20,000-Hz white-noise burst (70–80 dB sound pressure level) from one of two speakers, each located in front of the tangent screen and 10° to the right or to the left of the fixation point.

The CPVA task consisted of up to eight classes of trials, pseudorandomly interleaved. These were the same as classes 1–4 of the CP task, except that the stimuli could be visual or auditory. Specifically, two classes were memory saccade to left and right visual targets; two classes were memory saccade to left and right auditory targets; two classes had the A-B stimulus sequence, as in the CP task class 3, but with the modalities visual-then-auditory or auditory-then-visual; and two classes had the B-A stimulus sequence, in the visual-then-auditory or auditory-then-visual order. Four of the CPVA classes thus required a single change of plan, sometimes prompted by a visual stimulus and sometimes by an auditory one. The timing of the stimuli was slightly different in the CPVA task from the CP task. In all classes the first stimulus appeared after 750 ms of steady fixation, remained on for 750 ms, and was followed by a delay (M period) lasting at least 750 ms. The second stimulus, if present, also appeared for 750 ms and was followed by a 750-ms delay.

### *Data analysis*

The periods of interest in all tasks were the M periods following presentation of the stimuli. For analysis purposes we defined an M period as starting 100 ms after the offset of a stimulus and lasting until the extinction of the FP or appearance of the next stimulus, whichever came first. M periods thus lasted 300 ms in the MS and CP tasks, 1,150 ms in classes 1–4 of the CPVA task, and 650 ms in classes 5–8 of the CPVA task. A few neurons had M responses that were very large but clearly started after the 1st 100 ms of the delay period. For these neurons the beginning of the M period was adjusted manually to between 100 and 200 ms after the start of the delay period. Within each neuron's data set,

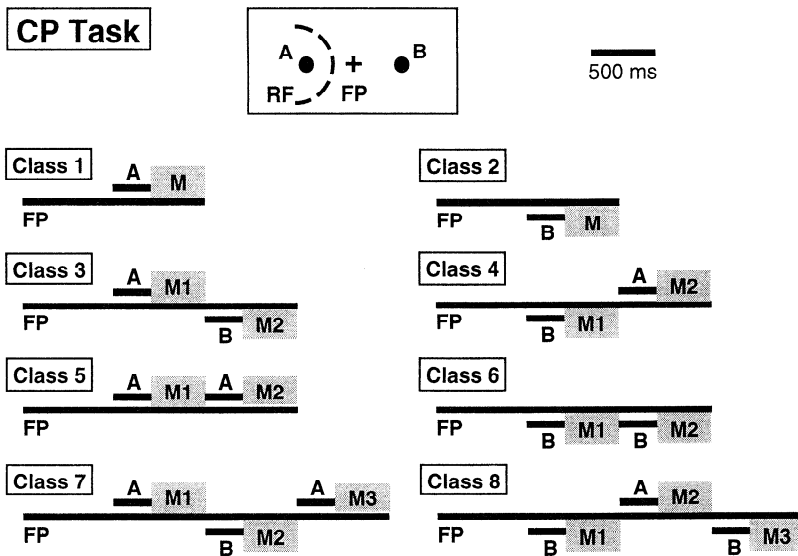


FIG. 1. Spatial and timing paradigms of the change of motor plan (CP) task. Panel at the top shows the spatial arrangement of the stimuli (●) relative to the fixation point (FP, +) and to the neuron's receptive field (RF, dotted semi-circle). The stimuli appeared either in the RF at location A or outside the RF at location B. For each class we show the appearance of a stimulus as a thick horizontal line. In all classes the FP appears 1st and remains on as 1, 2, or 3 stimuli appear in sequence. M, M1, M2, and M3 refer to the "memory," or delay, periods that follow each stimulus appearance.

however, a single definition of each period was applied to all classes of trials. For each class we computed the firing rate during M periods and compared it with the firing rate during the background period (BG) for that class. The BG period was a portion of the time preceding stimulus appearance, while the monkey fixated on the FP. It started at 300 ms from trial onset and ended at the appearance of the first stimulus (at 800 ms in the MS and CP tasks and 750 ms in the CPVA task).

We classified a neuron as excitatory if its M activity in the MS task was significantly greater than BG (2-tailed paired *t*-test,  $P < 0.05$ ) in at least one direction for a given target eccentricity. If the neuron was *not* excitatory and had M activity significantly smaller than BG ( $P < 0.05$ ), we classified it as inhibitory.

We conducted one-tailed paired *t*-tests to detect significant ( $P < 0.05$ ) increases (for excitatory cells) or decreases (for inhibitory cells) in M-period activity compared with BG-period activity in the various classes of the CP and CPVA tasks.

As a quantitative measure of a neuron's change in activity from one memory period to the next, we computed, for classes 3 and 5 of the CP task, the index  $I = (1 - M2/M1)$ , where M1 and M2 denote the net memory activity following the first and second target, respectively.

## RESULTS

### Data base

Our data base consists of 81 neurons isolated in area LIP in 3 hemispheres of 2 monkeys while the animals were performing the CP and CPVA tasks. The units were selected according to the following criteria: first, assignment to area LIP [as described in METHODS of the accompanying paper (Mazzoni et al. 1996a)]; second, presence of significant (paired *t*-test,  $P < 0.05$ ), spatially specific, M period activity in memory saccade tasks. These neurons are a subset of a larger group of neurons isolated in area LIP of our monkeys. Because we were also conducting related experiments in parallel with those reported here (Barash et al. 1991a,b; Bracewell 1991; Bracewell et al. 1991; Mazzoni 1994; Mazzoni et al. 1996b), not all the eligible units that we isolated were tested in the CP and CPVA paradigms. Sixty-two neurons were excitatory and 19 inhibitory.

We describe below the response patterns of the neurons we tested in the CP and CPVA tasks. For each task we will illustrate the response pattern of a typical neuron, followed by quantitative analysis of the responses of all the neurons in our sample.

### Visually cued change of plan: examples

We tested all neurons on classes 1–4 of the CP task. Figure 2 (*a–d*) shows the response pattern of an excitatory LIP neuron in these classes. This neuron had a RF in the left visual field. Figure 2*a* shows that target A evoked a clear memory period activity, whereas target B did not (Fig. 2*b*). In Fig. 2*c* we see the neuron's response in trials requiring a change of plan. Initially target A evokes a sustained response, which we suggest reflects the monkey's intention to make a saccade to A within the RF of the cell when the fixation spot is extinguished (as in Fig. 2*a*). However, while he is waiting, target B appears, indicating to the monkey that he must change his plan and prepare a saccade to B outside the neuron's RF. The eye movement traces indicate that this is what he does, after the FP is extinguished. Because he maintains fixation on the FP for as long as it is present, changes in firing rate cannot be attributed to eye movements. Target B appears to "cancel" the sustained M activity evoked by target A: the clear activity present during the first M period (M1) is absent in the second (M2). Conversely, in those trials in which target B is followed by target A, the neuron shows the opposite pattern of memory period activity (Fig. 2*d*). Target B, which is outside the RF, evokes no M activity (period M1). However, when target A appears briefly within the RF, indicating that the monkey must change his plan and program a saccade to A and not B, sustained activity is evoked (period M2).

We tested a subset of neurons ( $n = 31$ ) on all eight classes of the CP task. For these neurons, trials of all eight classes were pseudorandomly interleaved. Classes 5 and 6 were designed as control classes. The reduction in activity from the first (M1) to the second (M2) memory periods in class 3 might be due to processes unrelated to the change in saccade

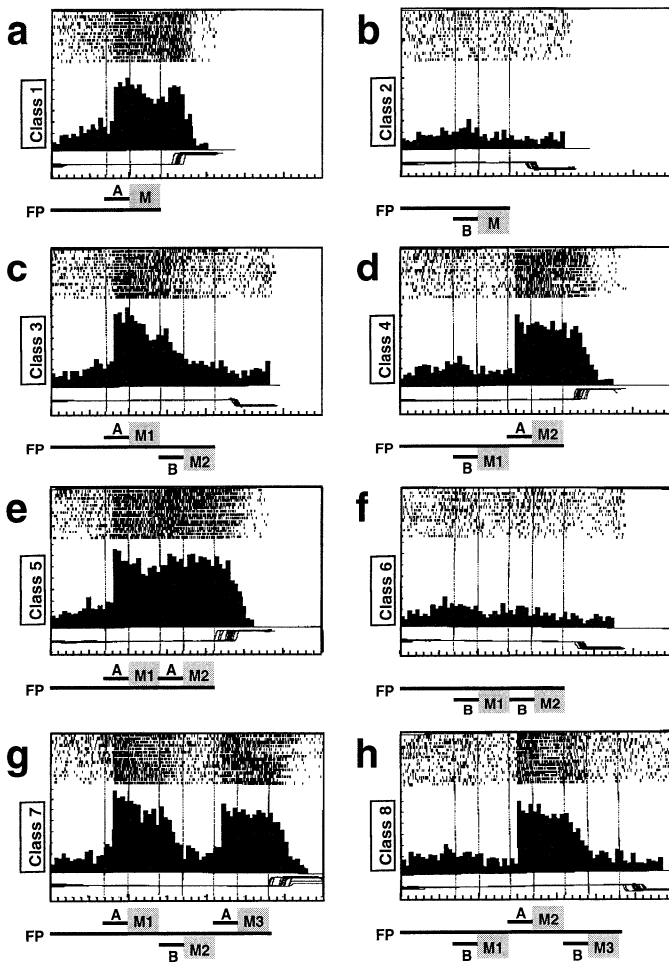


FIG. 2. Activity of an excitatory lateral intraparietal area (LIP) neuron in the CP task. The abscissa in each panel represents time (100 ms/division). Each panel contains, from top to bottom, rasters of tick marks representing the occurrences of action potentials, each row corresponding to 1 trial; a time histogram (binwidth, 50 ms) of the neuron's average rate of action-potential firing over all trials (25 Hz/division); and a trace of the monkey's vertical eye position (20°/division). Onset and offset times of stimuli during the trials are indicated both by the thin vertical lines within each panel and by the thick horizontal lines below each panel. Abbreviations are as in Fig. 1. *a* and *b*: simple memory saccade toward the RF (class 1) or away from it (class 2). *c* and *d*: single change of plan (A then B in class 3; B then A in class 4). *e* and *f*: no change of plan (controls; A then A in class 5; B then B in class 6). *g* and *h*: double change of plan (A-B-A in class 7; B-A-B in class 8). Trials with 1, 2, and 3 targets were pseudorandomly interleaved so that the monkey could not predict the target sequence or the required saccade in advance.

plan. For example, a neuron may simply adapt to repeated presentations of a visual stimulus. With classes 5 and 6 we tested whether any changes in M2 activity relative to M1 seen in change of plan trials were a nonspecific result of the fact that a target had recently appeared when the second target was presented. In these classes the target appeared twice in the same spot (at A in class 5, and at B in class 6), instructing the monkey to keep his saccade plan unchanged. In these trials the first plan formulated by the monkey was indeed the correct one. The second target therefore did not serve to change the monkey's plan. The appearance of the second target does not substantially alter the memory activity in either class of trial (Fig. 2, *e* and *f*), reflecting the monkey's maintenance of the same saccade plan. In the

final two classes (classes 7 and 8) we presented three targets in sequence while the monkey maintained fixation (A then B then A, or B then A, or B then A then B). In these trials the monkey was rewarded for making a saccade to the location of the last target to appear (as always); thus he presumably changed his plan twice because he was not aware how many stimuli would appear in the trial. Figure 2, *g* and *h*, illustrates the responses of the same LIP neuron in these classes. In class 7 (Fig. 2*g*) we see that target A, which appears in the RF, evokes memory activity (during period M1), which is cancelled by the appearance of B outside the RF (little activity in M2) only to reappear after A is presented once more (period M3). The converse pattern of activity is observed in class 8 (Fig. 2*h*), in which the sequence of targets is B-A-B.

We observed the same pattern of M period activity in neurons that had inhibitory M responses. Figure 3 shows the activity of such a neuron in the CP task. The cell's activity is inhibited by a stimulus in the upper left quadrant (target A; Fig. 3*a*) and is unaffected by a stimulus in the lower right quadrant (target B; Fig. 3*b*). In CP trials, the inhibition appears every time a saccade to target A is planned: in M1 of classes 3, 5, and 7 and M3 of class 7 (Fig. 3, *c*, *e*, and *g*). The inhibition is maintained when the plan for the up-left saccade is maintained (M2 of class 5; Fig. 3*e*) but is promptly cancelled every time the planned saccade is changed to a down-right one (M2 of classes 3 and 7, M3 of class 8; Fig. 3, *c*, *g*, and *h*).

#### Quantitative analysis

The M activity of the neurons of Figs. 2 and 3 is correlated with the monkey's saccade plan. It is significantly raised for the neuron of Fig. 2, and significantly depressed for the neuron of Fig. 3, whenever the monkey plans a saccade toward the neuron's RF. The activity of both neurons remains at background level whenever the saccade plan is for the opposite direction. The hypothesis that the M activity reflects the current saccade plan (motor plan hypothesis) predicts that this activity should change from one M period to the next within A-B, B-A, A-B-A, and B-A-B trials, and remain the same in A-A and B-B trials. Specifically, according to the motor plan hypothesis, M1 and M2 should be significantly different in classes 3, 4, 7, and 8, and not significantly different in classes 5 and 6. In classes 7 and 8, moreover, the activity in the M3 period should return to the same level as in M1. The M activity of the majority of neurons was consistent with this hypothesis in all classes of the CP task (Table 1; paired *t*-tests,  $P < 0.05$ ).

For several neurons the M3 response of class 7 was even stronger than in M1. We considered this consistent with the motor plan hypothesis. A possible explanation for this result may lie in the design of the CP task. Because no trials in this task had more than three target presentations, the monkeys were likely to know that the third target was certainly the goal of the required saccade. The enhancement of the M3 response over the M1 response may reflect the additional assurance that the motor plan of the M3 period would actually be executed.

To quantitate for each neuron how much its M response changed or stayed the same in the presence or absence of a plan

change, we computed an “activity-change” index. We defined this as  $1 - M2/M1$ , where M1 and M2 are the net responses, relative to the background activity level, during the first and second M periods of a given class, respectively. If the response turns off from one M period to the next, the index approaches the value 1 (100% change of activity). If the response remains the same the index approaches the value 0. Values  $>1$  indicate that the response changes sign (from inhibitory to excitatory or vice versa) from M1 to M2, and values  $<0$  mean that the memory response becomes even stronger in M2 compared with M1. Note that for inhibitory cells a strong response is indicated by a further decrease in activity. The same index formula can be used for positive and negative responses because the M1 and M2 responses appear as a fraction in the formula. For example, an inhibitory neuron whose response does not change (i.e. whose M1 and M2 are both negative and of similar value) would have

TABLE 1. Number of neurons whose M activity in the CP task is consistent/not consistent with the motor plan hypothesis

	Consistent With Motor Plan	Not Consistent With Motor Plan	Total
Class 3: M2 vs. M1	65 (80)	16 (20)	81 (100)
Class 4: M2 vs. M1	62 (77)	19 (23)	81 (100)
Class 5: M2 vs. M1	22 (71)	9 (29)	31 (100)
Class 6: M2 vs. M1	24 (77)	7 (23)	31 (100)
Class 7: M2 vs. M1	25 (81)	6 (19)	31 (100)
Class 7: M3 vs. M1	28 (90)	3 (10)	31 (100)
Class 8: M2 vs. M1	26 (84)	5 (16)	31 (100)
Class 8: M3 vs. M1	27 (87)	4 (13)	31 (100)

Values in parentheses are percentages. Excitatory M activity was consistent with the hypothesis if it decreased from M1 to M2 in classes 3 and 7, increased from M1 to M2 in classes 4 and 8, remained unchanged from M1 to M2 in classes 5 and 6, and returned at least to the same level from M1 to M3 in classes 7 and 8 ( $P < 0.05$ ). M, memory period; CP, change of motor plan; M1, M2, and M3, 1st, 2nd, and 3rd 400-ms delay periods, respectively.

the same index value (around 1.0) as an excitatory neuron whose M1 and M2 responses are similar to each other, because the negative signs of the inhibitory neuron’s responses would cancel each other in the formula.

We computed the activity-change index for class 3, in which the plan changes from a saccade in the neuron’s MF to one in the opposite direction, and for class 5, in which the plan remains unchanged as a plan for a saccade in the MF. If the M activity encodes the saccade plan, the index values for class 3 should be near 1.0 (if the response disappears) or  $>1.0$  (if the response becomes of the opposite sign in M2). The index values for class 3 for the neurons of Figs. 2 and 3, for example, were 1.11 and 1.05, respectively. In class 5, in which the plan does not change, the index values should be near 0 (if the response does not change) or negative (if the response is enhanced in M2). The index values for class 5 for the neurons of Figs. 2 and 3, for example, were  $-0.82$  and  $-1.03$ , respectively.

The index values for class 3 range from  $-0.28$  to 8.19, with a peak around 1.0 (median, 1.1; Fig. 4a), indicating that as a population the change in plan for a movement inside the RF to one outside the RF cancels most of the response. For 48 of the 81 neurons (59%), the response actually changed sign (index value  $>1.0$ ). Comparison of the two memory periods of class 3 revealed a significant difference in activity for 80% (65/81) of these neurons ( $P < 0.05$ ). The activity of most neurons thus reflected the change in saccade plan.

In class 5, on the other hand, the index values cluster around 0 (range,  $-4.36$  to 0.69; median, 0.0; Fig. 4b), no value being  $>0.7$ . The response was enhanced (index value  $<0.0$ ) for 16 of the 31 neurons (52%). Among the neurons tested, 71% (22/31) showed no significant decrease in activity in class 5 ( $P < 0.05$ ). The activity of most neurons tested thus remained largely unchanged or became reinforced in class 5, remaining consistent with the maintenance of the same oculomotor plan.

#### Visual-auditory change of plan

We have recently found that many units in area LIP that respond to visual stimuli in memory saccade tasks also re-

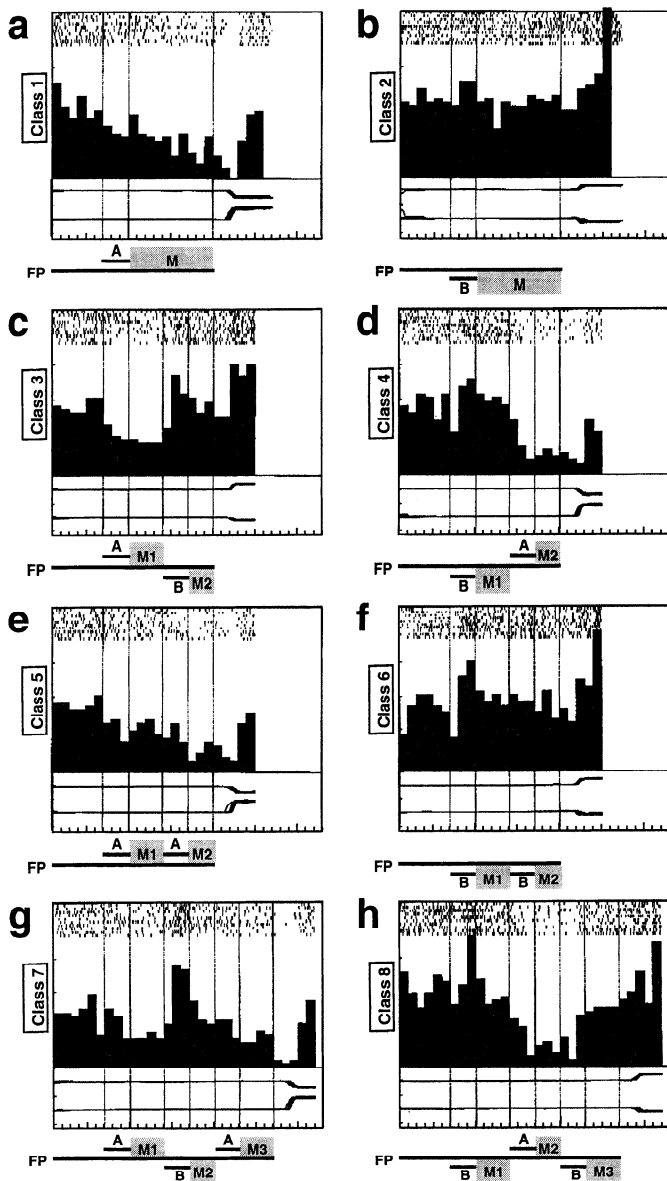


FIG. 3. Activity of an inhibitory LIP neuron in the CP task. Data are presented in the same format as in Fig. 2, using the same abbreviations. The histogram’s binwidth is 100 ms, and its vertical scale is 20 Hz/division. The eye position scale is  $15^\circ$ /division.

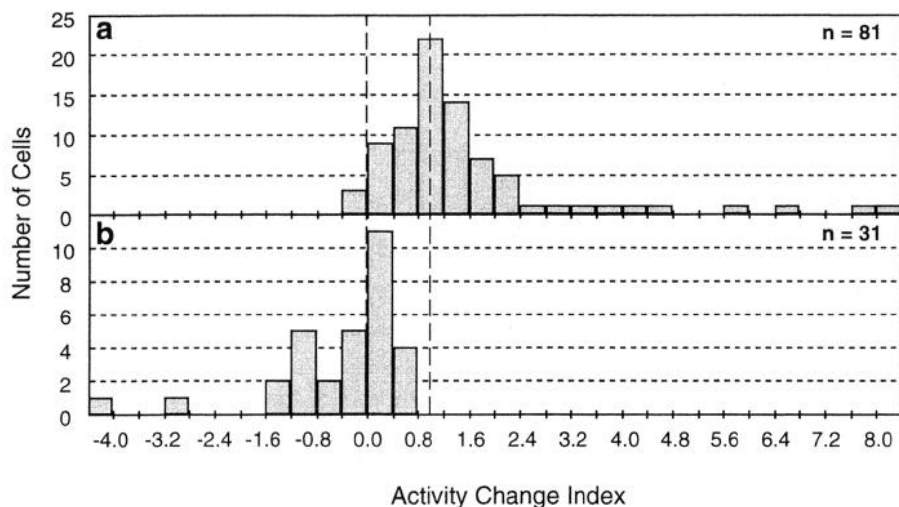


FIG. 4. Index of change of neural activity between the 1st and 2nd memory periods of the CP task. The index is computed as  $1 - M2/M1$ , where  $M1$  and  $M2$  are the average net firing rates, relative to the background rate, in the 1st and 2nd memory periods, respectively. Excitatory as well as inhibitory cells are included. *a*: index values in class 3 for all neurons in our data base ( $n = 81$ ). *b*: index values for class 5 for the neurons tested in classes 5–8 ( $n = 31$ ).

respond when auditory stimuli are used as cues to the location of the saccade goal (Bracewell et al. 1991; Mazzoni et al. 1996b). Several of these neurons have a similar pattern of responses in the visual and auditory versions of a memory saccade, that is, they respond in the same phases of the task (sensory, delay, and saccade periods) and with the same spatial selectivity regardless of stimulus modality. We predicted that if the M activity of these bimodal neurons reflects the monkey's saccade plan, then it should reflect changes of plan whether these are cued by visual or auditory stimuli.

We tested this prediction on a subset of LIP neurons ( $n = 22$ ) that had clear M responses in visual and auditory memory saccade trials. We recorded the activity of these neurons in the CPVA task. The activity of one of these neurons during four trial types of this task is shown in Fig. 5. This neuron had a significant M period response in rightward memory saccade trials, whether they were instructed by a visual cue (Fig. 5*a*) or by an auditory one (Fig. 5*b*). In the next two trial types, the monkey had to change his plan once. In Fig. 5*c* the first stimulus is auditory and falls outside the neuron's RF, eliciting no M response. The second stimulus is visual and falls in the RF, eliciting clear M activity. In Fig. 5*d* the first stimulus, outside the RF, is visual and produces no response. The second stimulus is auditory, in the RF, and it evokes strong M activity. The neuron's activity can thus be altered, without any overt behavior, using spatial cues from two modalities.

The responses to auditory and visual stimuli of the bimodal LIP neurons often differed in strength and tuning sharpness (unpublished observations). This may have been due to the fact that we did not attempt to match the saliency of stimuli in the two modalities. These differences, as well as minor difference in the metrics of the visual and auditory stimuli as outlined in the METHODS, made a quantitative analysis of the responses in the CPVA task inappropriate. Among the 22 neurons tested, activity in 8 clearly reflected change in plan; activity in a further 8 was in partial support of our hypothesis. Cells with strong M activity gave the clearest results in this paradigm.

#### DISCUSSION

We have previously shown (Barash et al. 1991a,b; Bracewell et al. 1991; Gnadt and Andersen 1988; Mazzoni

et al. 1996a) that the "memory" activity exhibited by an LIP neuron generally reflects the intention to make a saccade in a certain direction. The present results clearly demonstrate that alterations in the monkey's intentions, even in the absence of overt behavior, are manifested in altered LIP activity. Altogether, our experiments establish a role for area LIP that goes beyond the perceptual components of saccade execution. Its neurons express a physiological correlate of a monkey's plan to make a particular saccade. Because their activity is not obligatorily linked to the actual execution of a saccade, it does not encode a saccadic motor command, but rather the intention to execute a saccade. This intention can be altered as new information allows the monkey to

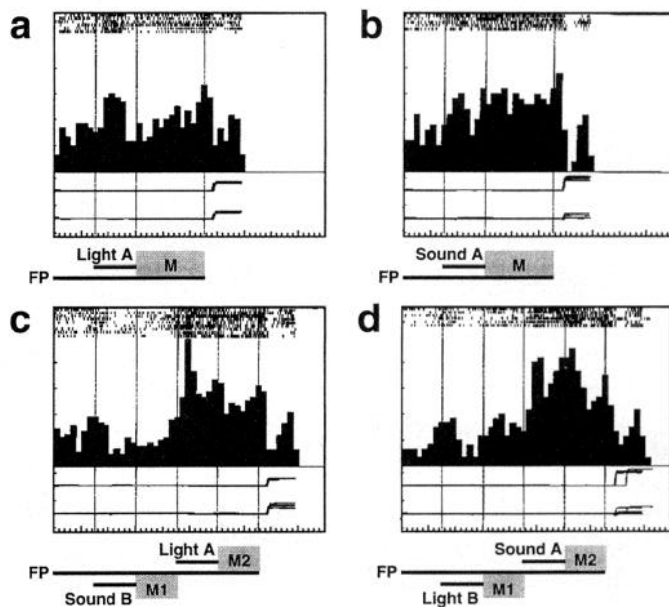


FIG. 5. Activity of an excitatory LIP neuron in the visual-auditory change of plan (CPVA) task. Data are presented in the same format as in Fig. 2, using the same abbreviations. The histogram's binwidth is 100 ms, and its vertical scale is 20 Hz/division. The eye position scale is  $10^\circ$ /division. In *a* and *b* a visual and an auditory stimulus, respectively, are presented in the neuron's RF. In *c* the auditory stimulus appears outside the RF and the visual one inside the RF, whereas in *d* the visual stimulus is outside the RF and the auditory stimulus inside.



update his motor plan. We also found that the M activity of many LIP neurons is evoked regardless of the modality of the cue to the saccade goal. Many cells in LIP are thus at least "bimodal," encoding plans for saccades to behaviorally relevant targets regardless of the modality through which these targets are localized.

### Controls

The monkeys had to maintain fixation (within 1° of the fixation spot) for as long as the fixation spot was present. Thus the alterations in activity during the M period(s) of the trials could not have been due to eye movements. Moreover, trials were pseudorandomly interleaved; thus the monkey did not know how many (or which) targets would be presented. To perform nearly flawlessly (as they did), they presumably had to plan to saccade to a target when it was presented, and change their plan if necessary later during the delay period.

Finally, classes in which the same target was presented twice (A-A and B-B trials) ensured that the monkeys could not use the appearance of a second target as a nonspatial cue to change their plans. These classes also controlled for adaptation as a possible cause of response reduction from one M period to the next.

### Other studies of changes of motor plan

Wise and colleagues have performed extensive studies of "motor set" (in our terminology, motor set is "motor intention") in the premotor cortex (PMC) (for review, see Wise 1985). Their most important finding is that, for most PMC neurons, the delay period activity is related to the direction of the forthcoming arm movement (the motor set), and not to the visuospatial cue ("instructional stimulus") indicating which response is required (Weinrich et al. 1984; Wise et al. 1983).

In a study in which the instructional stimulus was changed during the delay period, directionally specific motor set units showed concomitant changes in activity (Wise and Mauritz 1985). These results are similar to those of our "change of plan" study. One difference between their study and ours was that we did not present our targets (instructional stimuli) for the whole duration of the delay period, as did Wise and Mauritz. In theory, the changes in sustained activity observed by Wise and Mauritz (1985) might have been due to the changes in the continually present instruction stimulus. However, Wise and Mauritz (1985) also demonstrated that delay period activity did not depend on the continual presence of the instructional stimulus, which suggests that the continual presence of the instructional stimuli in their change of motor set experiment did *not* account for the change in activity with change in motor plan that they observed.

### Relationship between LIP activity and saccades

Our results suggest that LIP is involved in the planning of saccades, and rather indirectly in their production. Activity in LIP is not necessarily followed by a saccade. LIP activity may vary in the absence of overt eye movement behavior. It is possible that LIP projections to superior colliculus (and perhaps to the frontal eye fields) may raise the level of

excitation there such that a "trigger" signal can more easily evoke a particular saccade. In this regard it is interesting that LIP cells often show a saccade-related burst of spikes with a frequency substantially higher than that during the sustained, elevated M activity (e.g., see Fig. 2a). This burst may serve as part of the trigger signal suggested above. The initial source of this saccade response is unknown and would require further experiments to determine the first locations in the brain to generate it.

The activity in other high-order motor areas typically also has a nonobligate relation to movement (reviewed in Georgopoulos 1991). This is true even of the cortical motor neurons of the primary motor cortex, the "upper motor neurons" of many a neurology textbook. Evarts (1981, 1986), Cheney and Fetz (1980), and Lemon (1988) have shown that the relationship between their firing and muscle activity is conditional and complex. In addition, some neurons in the motor cortex fire during an instructed delay period of a delayed response task (e.g., Evarts and Tanji 1974). It is thus perhaps better to think of high-order areas in terms of motor planning, and to "consign" the details of execution to lower regions such as the brain stem (for eye movements, see Wurtz and Goldberg 1989 for review) and the spinal cord (for limb movements, see Alsterneck et al. 1981; Georgopoulos and Grillner 1989).

We thank C. Cooper, G. Robertson, R. Keough, and S. Marchetti for technical and administrative assistance and L. Snyder for comments on the manuscript.

This work was supported by National Eye Institute Grant EY-05522 and Office of Naval Research contract N00014-89-J1236. R. M. Bracewell was supported in part by Surdna and Whitaker Health Sciences Fund fellowships. P. Mazzoni was supported in part by a Medical Scientist Training Program award.

Address for reprint requests: R. A. Andersen, Division of Biology, 216-76, California Institute of Technology, Pasadena, CA 91125.

Received 27 April 1994; accepted in final form 7 February 1996.

### REFERENCES

- ALSTERNACK, B., LUNDBERG, A., NORSELL, U., AND SYBIRSKI, E. Integration on descending motor pathways controlling the forelimb in the cat. IX. Differential behavioral effects after spinal cord lesions interrupting defined pathways from higher centres to motoneurons. *Exp. Brain Res.* 42: 299–318, 1981.
- ANDERSEN, R. A., ASANUMA, C., AND COWAN, W. M. Callosal and prefrontal associational projecting cell populations in area 7a of the macaque monkey: a study using retrogradely transported fluorescent dyes. *J. Comp. Neurol.* 232: 443–455, 1985.
- ANDERSEN, R. A., ASANUMA, C., ESSICK, G., AND SIEGEL, R. M. Corticocortical connections of anatomically and physiologically defined subdivisions within the inferior parietal lobule. *J. Comp. Neurol.* 296: 65–113, 1990.
- ANDERSEN, R. A., ESSICK, G. K., AND SIEGEL, R. M. Neurons of area 7a activated by both visual stimuli and oculomotor behavior. *Exp. Brain Res.* 67: 316–322, 1987.
- BARASH, S., BRACEWELL, R. M., FOGASSI, L., AND ANDERSEN, R. A. Interactions of visual and motor-planning activities in the lateral intraparietal area (LIP). *Soc. Neurosci. Abstr.* 2: 1203, 1989.
- BARASH, S., BRACEWELL, R. M., FOGASSI, L., GNADT, J. W., AND ANDERSEN, R. A. Saccade-related activity in the lateral intraparietal area. I. Temporal properties; comparison with area 7a. *J. Neurophysiol.* 66: 1095–1108, 1991a.
- BARASH, S., BRACEWELL, R. M., FOGASSI, L., GNADT, J. W., AND ANDERSEN, R. A. Saccade-related activity in the lateral intraparietal area. II. Spatial properties. *J. Neurophysiol.* 66: 1109–1124, 1991b.
- BLATT, G. J., ANDERSEN, R. A., AND STONER, G. R. Visual receptive field

- organization and cortico-cortical connections of the lateral intraparietal area (area LIP) in the Macaque. *J. Comp. Neurol.* 299: 421–445, 1990.
- BRACEWELL, R. M. *On the Posterior Parietal Cortex and Saccadic Eye Movements* (PhD dissertation). Cambridge, MA: MIT, 1991.
- BRACEWELL, R. M., BARASH, S., MAZZONI, P., AND ANDERSEN, R. A. Neurons in the macaque lateral intraparietal cortex (LIP) appear to encode the next intended saccade. *Soc. Neurosci. Abstr.* 17: 1282, 1991.
- CHENEY, P. D. AND FETZ, E. E. Comparable patterns of muscle facilitation evoked by individual corticomotoneuronal (CM) cells and by single intracortical microstimuli in primates: evidence for functional groups of CM cells. *J. Neurophysiol.* 53: 786–804, 1980.
- EVARTS, E. V. Role of motor cortex in voluntary movements in primates. In: *Handbook of Physiology. The Nervous System. Motor Control*. Bethesda, MD: Am. Physiol. Soc., 1981, sect. 1, vol. II, p. 1083–1120.
- EVARTS, E. V. Motor cortex output in primates. In: *Cerebral Cortex*, edited by E. G. Jones and A. Peters. New York: Plenum, 1986, vol. 5.
- EVARTS, E. V. AND TANJI, K. Gating of motor cortex reflexes by prior instruction. *Brain Res.* 71: 479–494, 1974.
- GEORGOPOULOS, A. P. Higher order motor control. *Annu. Rev. Neurosci.* 14: 361–377, 1991.
- GEORGOPOULOS, A. P. AND GRILLNER, S. Visuomotor coordination in reaching and locomotion. *Science Wash. DC* 245: 1209–1210, 1989.
- GNADT, J. W. AND ANDERSEN, R. A. Memory related motor planning activity in posterior parietal cortex of macaque. *Exp. Brain Res.* 70: 216–220, 1988.
- GOODALE, M. A. AND MILNER, A. D. Separate visual pathways for perception and action. *Trends Neurosci.* 15: 20–25, 1992.
- HIKOSAKA, O. AND WURTZ, R. H. Visual and oculomotor functions of monkey substantia nigra pars reticulata. III. Memory-contingent visual and saccade responses. *J. Neurophysiol.* 49: 1268–1284, 1983.
- LEMON, R. The output map of the primate motor cortex. *Trends Neurosci.* 11: 501–506, 1988.
- LYNCH, J. C., GRAYBIEL, A. M., AND LOBECK, L. J. The differential projection of two cytoarchitectonic subregions of the inferior parietal lobule of macaque upon the deep layers of the superior colliculus. *J. Comp. Neurol.* 253: 241–254, 1985.
- MAZZONI, P. *Spatial Perception and Movement Planning in the Posterior Parietal Cortex* (PhD dissertation). Cambridge, MA: MIT, 1994.
- MAZZONI, P., BRACEWELL, R. M., BARASH, S., AND ANDERSEN, R. A. Motor intention activity in the macaque's lateral intraparietal area. I. Dissociation of motor plan from sensory memory. *J. Neurophysiol.* 76: 1439–1456, 1996a.
- MAZZONI, P., BRACEWELL, R. M., BARASH, S., AND ANDERSEN, R. A. Spatially tuned auditory responses in area LIP of macaques performing delayed memory saccades to acoustic targets. *J. Neurophysiol.* 1–19, 1996b.
- WEINRICH, M., WISE, S. P., AND MAURITZ, K. A neurophysiological analysis of the premotor cortex in the monkey. *Brain* 107: 385–414, 1984.
- WISE, S. P. The primate premotor cortex: past, present and preparatory. *Annu. Rev. Neurosci.* 8: 1–19, 1985.
- WISE, S. P. AND MAURITZ, K. Set related neuronal activity in the premotor cortex of rhesus monkeys: effects of changes in motor set. *Proc. R. Soc. Lond. Ser. B Biol. Sci.* B223: 331–354, 1985.
- WISE, S. P., WEINRICH, M., AND MAURITZ, K. Motor aspects of cue-related neuronal activity in premotor cortex of the rhesus monkey. *Brain Res.* 260: 301–305, 1983.
- WURTZ, R. H. AND GOLDBERG, M. E. *The Neurobiology of Saccadic Eye Movements*. Amsterdam: Elsevier, 1989.