Auditory Spatial Discriminatory and Mnemonic Neurons in Rat Posterior Parietal Cortex

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Nakamura, Kiyomi. Auditory spatial discriminatory and mnemonic neurons in rat posterior parietal cortex. J. Neurophysiol. 82: 2503–2517, 1999. The present study was designed to investigate whether the rat posterior parietal cortex is involved in the perception and the representation of the auditory space. We recorded single neural activity in the posterior parietal cortex of rats that performed a directional delayed nonmatching-to-sample task. In the task, cue tones were presented in one of six speakers that were placed symmetrically around the rats. “Familiar tones” were those repeatedly used in the course of behavioral training. Novel tones were presented only during the unit recording time and less frequently used (e.g., only once in alternate weeks). The responses of the posterior parietal cortex neurons were typically tested with familiar cue tones while the rats were situated in a particular geomagnetic orientation. The same cells were further tested while the rats were reoriented by 180°, or by novel cue tones. As the task included a delay period, in which the cue tone was removed, the rats had to maintain the directional information of the cue tones during this period to maximize the reward rates. A well-trained rat could perform the task with 85% success. We found two major types of neurons intermixed in the rat posterior parietal cortex. One type (n = 14) mainly discriminated the direction of the cue tones, whereas the other (n = 36) carried a mnemonic value of the cue tones while the tones were removed. The former responded only during the cue tone period (discriminatory neurons), whereas the latter responded during the cue tone period and the delay period (mnemonic neurons). These cells also exhibited broad directional tuning. The results agreed with previous studies, suggesting that a population coding scheme exists in the posterior parietal cortex. When the cells were tested with novel tones or when the rats were rotated through 180°, the vast majority of the cells exhibited a directional tuning similar to those under the control conditions. Three quarters (18/24) of the cells that exhibited a mnemonic characteristic persisted in their directional preference when the rat’s orientation was changed (12/17 neurons) or when an unfamiliar auditory stimulus was used (6/7 neurons). Half of the discriminatory neurons (4/8 neurons) persisted in their directional preference. These results, consistent with previous behavioral studies, suggest an allocentric representation of the auditory processing in this area. Furthermore, when the rat was reoriented or an unfamiliar cue tone was used, both the average and peak directional responses were enhanced in more than half of the mnemonic or discriminatory neurons. These results support the frequency-dependent neocortical gating hypothesis of the entorhinal hippocampal loop.

INTRODUCTION

Across species, the parietal cortex is considered to be involved in spatial information processing related to many frames of reference (spatial coordinates) (Pouget and Sejnowski 1997). In rats, an area in the occipital cortex located anterior to the primary visual cortex (Oc1) and posterior to the parietal cortex (Par 1) is considered to be an association cortex that corresponds to the posterior parietal cortex of primates (Paxinos and Watson 1986). This area is named variously Krieg’s ares 7 (Krieg 1946), rostral Oc2M (Zilles 1985), or area AM (Olavarria and Montero 1981) and is believed to be polysensory (Andersen et al. 1997; Toldi et al. 1986).

Previous lesion-behavioral studies in both primates and rodents have shown that the posterior parietal cortex is closely related to allocentric spatial information processing (Kesner et al. 1989, 1992; Kolb et al. 1994). Neurophysiological studies in monkeys showed that the visual receptive field of posterior parietal neurons were in retinal (eye-centered) coordinates, but were strongly modulated by both eye and head positions (Andersen et al. 1985; Brotchie et al. 1995). The modulatory effects of eye and head positions were equivalent. Thus their study suggests that the posterior parietal cortex is a stage of the distributed representation of space in body-centered coordinates. Another study of monkeys showed that the neuron in the anterior bank of the parietooccipital sulcus (area V6 or PO) is related to head-centered (craniotopic) encoding (Galletti et al. 1993). The neural response was fixed to a specific position within a view, irrespective of the eye gaze direction. However, this study did not test the neural response when rotating (or moving) the monkey’s head and body. Thus it is impossible to determine whether the neurons encoded allocentric or egocentric spatial cue location.

In rodents, the head direction (HD) cells in the posterior parietal cortex and other brain areas respond when the rat’s body axis is oriented to a specific direction, irrespective of the animal’s location (Chen et al. 1994a,b). This can be interpreted as the HD cells coding the allocentric body orientation relative to the external spatial cue arrangement. The gain (or tuning) of angular-motion cells in rodents are modulated by the animal’s behavior (i.e., left or right turning by either active or passive movement) and by multimodal stimulation, i.e., visual, vestibular or proprioceptive inputs (Chen et al. 1994a,b; Chen and Nakamura 1998). From these studies, it is obvious that the posterior parietal cortex in rodents is related to spatial discriminative processing, but it is not clear whether the same area is related to the spatial mnemonic functions revealed in the active neural activity.

In mammals, the mnemonic functions revealed in the active neural activity have been tested by tasks requiring delayed behavioral responses, i.e., delayed nonmatching-to-sample (DNMS) and delayed matching-to-sample (DMS) tasks (Cahusac et al. 1989; Squire et al. 1988; Vidyasagar et al. 1993). The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
1991); continuous DNMS task (Otto and Eichenbaum 1992; Sakurai 1990; Willner et al. 1993); serial multiple object-place memory tasks and delayed spatial response tasks (Cahusac et al. 1989; Miyashita et al. 1989; Rolls et al. 1989). Persistent neural activity during the delay period is obvious evidence of the active neural mnemonic function. The continuous DNMS task and the serial multiple object-place memory task cannot accurately define activity during a delay period evaluated from the spontaneous (baseline) control activity. In a recent study of spatially tuned responses in area LIP, monkeys performed the delayed memory saccades task to acoustic and visual targets (Mazzoni et al. 1996). The neural responses were bimodal in both the stimulus and delay periods in many neurons. Furthermore, the spatial tuning for the auditory and visual modalities were almost the same. In rodents, however, neurophysiological studies of the delayed spatial mnemonic function in the posterior parietal cortex are rare (Chen et al. 1994a,b; Chen and Nakamura 1998).

There is a hypothesis that a frequency-dependent neural reverberation in the entorhinal cortex (EC)–hippocampus (HF) loop can be initiated by increased input from the neocortex (Chrobak and Buzsaki 1994; Jones 1993). It is believed that the neural information flow from the parietal cortex via the the parahippocampal, perirhinal, and entorhinal cortical areas to HF is essential for learning and memory of spatial information. The spatial DMS task shows that unfamiliar spatial stimuli are important in activating the medial temporal memory consolidation system (Cahusac et al. 1989; Miyashita et al. 1989; Otto and Eichenbaum 1992; Rolls et al. 1989). Because the posterior parietal cortex is the supramodal association cortex that interferes between the multimodal sensory inputs and the medial temporal memory consolidation system, it is interesting to know whether the posterior parietal cortex, by increasing its activity, has some gating role to interfere with the medial temporal memory consolidation system.

In the present study, the neural activity in the posterior parietal cortex was analyzed as a rat performed a spatial working memory task; directional delayed nonmatching-to-sample (dDNMS) in normal and altered orientations and with familiar and unfamiliar acoustic stimuli. The present study showed two different types of spatially tuned neurons: directional discriminatory and directional mnemonic neurons. Some of these were allocentric. The directional mnemonic neurons showed delay period activity, but the directional discriminatory neurons did not. The neural responsiveness of some of these neurons was enhanced after reorientation or with unfamiliar acoustic stimulus.

METHODS

The basic recording techniques of neural activity from awake and chronic rats are described in previous papers (Nakamura and Ono 1986; Nakamura et al. 1987; Ono et al. 1985, 1986). In the present experiment, to obtain a stable unit recording during the rotation and shift of the rat, horizontally movable recording microelectrodes developed by the author were used.

Animals and surgery

The subjects were five male Sprague-Dawley rats weighing 300–400 g. Each rat was housed individually in a cage with free access to laboratory chow and water in a temperature controlled room (23°C) with a 24-h light-dark cycle (on at 07:00, off at 19:00). The surgical procedures were essentially the same as previously described (Nakamura and Ono 1986; Nakamura et al. 1987; Ono et al. 1985, 1986). During surgery under pentobarbital sodium anesthesia (40 mg/kg ip), a small hole was opened and a bipolar stimulating electrode for brain stimulation reward was implanted in the posterior lateral hypothalamicus (LHA) at coordinates (A, −4.5 to −5.0; L, 1.4 to 1.8; V, 8.0 to 8.8 mm from the bregma) (Paxinos and Watson 1986). After implanting the stimulating electrode, six screws were implanted in the skull as anchors for the dental cement cap, which was adjusted to restrain the head in the stereotaxic apparatus during training and recording sessions. After surgery, the rats were returned to their home cages, and 10–20 days were allowed for recovery. The day before unit recording, a 2-mm diameter hole was drilled, under ketamine anesthesia (15 mg/kg im), in the skull over the intended recording site (A, −3.0 to −6.0; L, 2.0 to 3.5; V, 1.2 to 2.2 mm), and the animals were again returned to their home cages.

Training, recording procedures, and data analysis

Before training and recording sessions, each rat was deprived of food and water for −12 h. The screening and training are described in the previous papers (Nakamura and Ono 1986; Nakamura et al. 1987; Ono et al. 1985, 1986). During training and later recording sessions, the rat’s head was restrained painlessly in a stereotaxic apparatus. The stereotaxic apparatus was mounted on a conventionally available stage that could be controlled by computer to rotate and move horizontally (α15 and AS2, THK, Tokyo, Japan). The rats were trained to perform a spatial working memory task, dDNMS. Six speakers (S1–S6) surrounded the field at the same height in a hexagonal arrangement. The distance between the animal and each speaker was equal (80 cm) for all speakers. Figure 1 shows the experimental apparatus and the time sequence of the dDNMS task. In the dDNMS, the first (sample) and the second (match/nonmatch) cue tone (CT) were directed at the rat with a fixed time delay (2 s) from either the same location (matched pair) or different locations (nonmatched pair). The first and the second CTs were identical in the frequency spectrum. The rat compared the direction of the two CTs and needed to immediately lick the spout for a nonmatched pair or postpone the lick for a matched pair to receive a reward. The reward was either intracranial brain stimulation (ICSS) or 20 μl of sucrose solution (0.3 M). During the training and recording, two different kinds of familiar CTs were used. One CT was associated with brain stimulation reward, and the other was associated with sucrose solution. During unit recording, occasionally a new CT programmed by computer was used to test responsiveness to an unfamiliar cue tone. A total of five CTs (2 familiar and 3 unfamiliar CTs) were used in general. Of these, four CTs were sinusoidal waves that were arranged not to be harmonics of each other, and the remaining one CT was a broadband frequency spectrum wave. The two familiar CTs were sinusoidal waves among the four sinusoidal CTs, which were predetermined randomly for each rat and were different from rat to rat. The three unfamiliar CTs were the remaining two sinusoidal CTs and one broadband CT.

The sound signals were generated by a programmable synthesizer (Sound Orchestra-VS, SNE, Tokyo, Japan). The synthesized signals were amplified by independent amplifiers and connected to their respective speakers (ATC-SP14, Audio-technica, Tokyo, Japan). Calibration and monitoring of the sound field was performed using an omnidirectional microphone placed directly just above the animal’s head and facing the speakers. The microphone was connected to a sound level meter (NL-18, Rion, Tokyo, Japan) and to an A/D converter (EC-9840, Elmec, Tokyo, Japan). The respective CTs with 1 kHz bandwidth were A/D converted with 40-kHz sampling rate and the frequency spectra of respective CTs were calculated up to 20 kHz using fast Fourier transform analyzing software (WAAP-WIN, Elmec, Tokyo, Japan). The frequency spectra of the CTs from respective speakers are shown in Fig. 2. The sound pressure levels (SPL)
measured in the experimental circumstances were expressed in decibels (dB). They were compensated for the transmission characteristics of the speakers and the sound delivery pathways. The sound levels measured by the sound level meter were equalized to 80 ± 0.7 dB across all six speakers in all CTs used.

Under short-acting local anesthesia (a few drops of 1% procaine), a horizontally movable tungsten microelectrode (tip length and diameter, 5 μm × 1 μm, 1–5 MΩ) was inserted vertically through the dura into the intended recording site in the posterior parietal cortex. Single-unit activity was recorded stably from the posterior parietal cortex of a conscious rat using the movable microelectrode. This electrode effectively absorbed instantaneous head acceleration or vibration due to rotation or movement of the stage and due to behavioral responses. The horizontally movable microelectrodes had been previously used effectively in the unit recording of gustatory taste neurons in the nucleus of the solitary tract of a conscious rat (Nakamura and Norgren 1993). Using the microelectrodes, only one penetration for each rat was made in a day unit recording time. Several penetrations (ranging from 5 to 9) were made for each rat during the 2- to 3-mo recording period. The unit recording from each rat was made no more than once in a week using a familiar CT. The unfamiliar CTs were presented only during the unit recording time and were used no more than once in alternative weeks. Because there are three unfamiliar CTs and they were used less frequently, the rat would be unlikely to acquire any degree of familiarity

In the normal (familiar) condition, the rat’s head was located in the center and oriented to S2. During unit recording, after neural activity was tested in familiar conditions, the rat was then either rotated to a different orientation (altered orientation) or retested with an unfamiliar CT (unfamiliar acoustic condition) with the same dDNMS task. When the rat was rotated, the distance between the animal and each speaker was still equal and unchanged for all speakers. Thus the sound levels and frequency spectra were identical even when the rat was rotated.

Originally, the neural firing data were stored every 20 ms in the analyzing computer. Both neural and behavioral data were summed in histograms of successive 100-ms bins for 11 s (a pretest control period (2.0 s), sample CT (1.0 s), delay (2.0 s), match/nonmatch CT (1 s), and behavioral and rewarding stimulation period (5.0 s)). The neural responses were calculated for every second, expressed as spikes per second. The average firing rate for the baseline was calculated from the data of the pretest control period (2.0 s). The mean directional neural responses in each period were calculated from the data of sample CT (1.0 s), delay (2.0 s), match/nonmatch CT (1 s), and expressed as spikes per second. The response significance (excitation or inhibition) was determined by ANOVA between the pretest control and each directional stimulus period. The significance level was \( P < 0.05 \). There are two ways to represent directional raster displays and histograms of the neural responses, i.e., one based on the first (sample) tone direction and the other based on the second (matched or nonmatched) tone direction. Basically, the classification and analysis of directional responses in the present study was done separately in the two periods. The classification and analysis based on the first CT directions were from the beginning of the first CT and during the delay just before the onset of the second CT, and those based on the second CT directions were from the beginning and after the second CT onset. Although both types of directional responses represented in the raster displays and histograms were used, the figures in the present paper show only the former one alone; it was difficult to combine both type of raster displays and histograms on the same time axis in the case of nonmatched trials. Because the neural responses to sample and matched/nonmatched CTs were similar in the spatial tuning in almost all cases when the CT influenced these neurons, the analysis of neural response to CT in the present study represents the responses to the sample CT. A detailed analysis of the response comparison between sample and matched/nonmatched CTs will be reported separately.

For the statistical test of functional fitting of the directional tuning curve made from the neural responses to CT, both a first degree sinuosoidal regression and a Gaussian curve regression were performed on the directional neural responses (SYSTAT, SYSTAT). A measure of the goodness of the regression fit is the coefficient of the determination, \( R^2 \), which is the proportion of the total variation that is explained by the regression.

**Histology**

At the end of each recording session, the coordinates of the recording site were precisely measured from the center of the coordinate indicator tube that had been implanted at the time of surgery. After the final recording, the rats were reanesthetized and replaced in the stereotaxic apparatus for the histological verification of the recording and stimulating sites. These procedures are essentially the same as previously described (Nakamura and Ono 1986; Ono and Nakamura 1985; Ono et al. 1985, 1986). A steel electrode, insulated except at the tip (30 μm), was placed at four to six sites 0.2 mm beyond the boundaries of the area from which neurons had been isolated from each rat. These steel electrode sites were also precisely measured from the center of the coordinate indicator tube. Each steel electrode site was marked by an iron deposit created by passing a 20-μA positive current for 30 s. The stimulating site was also marked by an iron
In total, 234 neurons were recorded during dDNMS. Of these, 128 neurons were in the Oc2M, i.e., Oc2MM and Oc2ML. This paper reported the activity of the 128 neurons in the Oc2M. After the activity of these neurons were tested by familiar CT in the normal orientation [i.e., normal (familiar) condition], 33 neurons were further tested either after reorientation (21 neurons) or with unfamiliar CTs (12 neurons). Tables 1 and 2 summarize these neural responses.

Of 128 posterior parietal cortex neurons, 50 responded to the directional CT (43 excitation, 7 inhibition). Of these, 48 neurons responded to the spatial tones presented from one to several directions ranging from 1 to 5 directions. Only two neurons responded to tones from all six directions, but the response strength of the two neurons depended on the CT direction. Thus the 50 neurons had differential responses to directional CT. The mean number of the response directions to CTs was 1.89 ± 1.33 (mean ± SD, n = 50), ranging from one to six directions.

During the delay period, 37 neurons showed significant activity (33 excitation, 4 inhibition). Among the 50 CT responsive neurons, 36 neurons had significant activity during the delay period (33 excitation, 3 inhibition), and 14 neurons did not have significant activity during the delay period. Among the remaining 78 CT nonresponsive neurons,
only one had significant activity during the delay period (inhibition). Thus more than two-third of CT responsive neurons (36/50) had significant activity during the delay period ($P < 0.001$, Pearson’s $\chi^2$ test). Furthermore, in almost all the neurons (35/36), the response to the CT was similar in sign to the responses during the delay period (33 excitation, 2 inhibition). For the sake of convenience, the 36 neurons responsive both to CT and during the delay were named directional mnemonic neurons, and the other 14 neurons responsive only to CT were named directional discriminatory neurons in this paper. The typical neural responses of these neurons are shown in Figs. 3 and 4. The neural responses of a directional discriminatory neuron are shown in Fig. 3. The neuron responded to CTs presented from left-anterior and forward directions (S3 and S2) but did not show significant activity during the delay period subsequent to any directional CT. Figure 4 shows the responses of a directional mnemonic neuron. The neuron responded to the CTs from forward and right-anterior directions (S2 and S1). The neuron also responded during the delay period subsequent to CT from S1.

The mean numbers of the response directions of the directional mnemonic neurons were $2.07 \pm 1.37$ ($n = 36$) to CT and $1.60 \pm 1.13$ ($n = 36$) during the delay period, whereas the mean number of the response directions of the directional discriminatory neurons to CT was $1.65 \pm 1.12$ ($n = 14$).

Neural responses in reoriented orientations

Twenty-one neurons were tested in both the normal and altered orientations using familiar CT. The responsiveness to CT was compared in both normal and altered orientations. Of the 21 neurons, 18 neurons responded to the directional CT in both normal and altered orientations. In many neurons (89%, 16/18), the response directions were similar (13 were excited, and 3 were inhibited in both orientations). Three neurons responded to CT in either orientation (1 neuron in normal orientation, and 2 neurons in altered orientation). Thus many neurons persisted in their responsiveness to CT even after reorientation. Tables 1B and 2A summarize these neural responses.

When the responsiveness during the delay was compared in both normal and altered orientations, 12 neurons responded in both cases. In all but one neuron (92%, 11/12), the delay period responsiveness was similar (excited in both orientations). During the delay period, one neuron responded only in normal orientation and four neurons only in altered orientation; the remaining four neurons responded neither in normal nor altered orientations. Thus many neurons persisted in their responsiveness during the delay period even after reorientation.

When the neural responsiveness was summed in both normal and altered orientations, more than two-thirds of the CT responsive neurons showed significant activity during the delay period (Table 2A). Of the 21 neurons responsive to CT in either

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or both normal and altered orientations, 17 neurons also showed significant activity during the delay period in either or both orientations (Table 2A). Four CT responsive neurons did not respond during the delay period in either orientation.

The typical neural responses in normal and altered orientations are shown in Figs. 5 and 6. The neuron shown in Fig. 5 is a directional discriminatory neuron; unit 31 in Table 2A. The neuron responded to CTs from directions S1, S4, S5, and S6 but showed no response during the subsequent delay period when the rat was oriented toward S2 in normal orientation (Fig. 5, A and B). When the rat was reoriented toward S5, the neuron responded neither to CT nor during the delay (Fig. 5, C and D). The neuron shown in Fig. 6 corresponds to a directional mnemonic neuron; unit 19 in Table 2A. The neuron responded to CT from direction S3, and during the delay period subsequent to CT from S3, when the rat was in the normal orientation (Fig. 6, A and B). The neuron still responded to the CTs from S2 and S3, and during the subsequent delay period after CT from S3, when the rat was reoriented to S5 (Fig. 6, C and D). Thus the responses to CT and during the delay were allocentric. It is improbable that the CT from S3 speaker had unique spectral characteristics that preferentially excited this neuron, because the level and frequency responses of all speakers were calibrated and equalized.

The mean numbers of the response directions of the neurons in the normal orientations were 2.50 ± 1.60 (n = 19) for the CT and 1.65 ± 0.85 (n = 13) during the delay period. They were 2.40 ± 1.30 (n = 20) for the CT and 1.38 ± 0.65 (n = 16) during the delay period in the altered orientations.

We compared the response strength of the average and peak neural responses in the normal and reoriented conditions. In the comparison, the corrected responses for each period (CT and delay) were used. The corrected responses were calculated by subtracting the mean baseline (control) activity from the mean actual activity in each period. The average and peak response enhancement indices were obtained by dividing the average and peak responses in the altered orientation by those responses in the normal condition. The average response enhancement indices for the neuron shown in Fig. 6 were 1.42 for CT, and 1.36 during the delay period. The peak response enhancement indices were 1.38 for the CT and 1.60 during the delay period. The response enhancement indices for the other neurons that responded to CT (or during the delay period) in both orientations are shown in Fig. 9A. The response enhancement indices for CT ranged from 0.45 to 2.36 (1.27 ± 0.54, n = 18) for the average response and from 0.67 to 2.36 (1.23 ± 0.50, n = 18) for the peak response. The response enhancement indices during the delay period ranged from 0.62 to 2.50 (1.18 ± 0.52, n = 12) for the average response and from 0.51 to 2.10 (1.15 ± 0.50, n = 12) for the peak response.

In many neurons, the response enhancement index for the CT was more than 1.1 for both the average response (12/18 neurons) and peak response (10/18 neurons). This indicates that the response to CT in many neurons was enhanced in the
FIG. 5. Raw raster displays, histograms, and directional tuning of a discriminatory Oc2M neuron in normal (A and B) and altered orientations (C and D). A and B: responses in normal orientation. The neuron responded to CTs presented from the right and rear (S1, S4, S5, and S6). The neuron did not show significant activity during the delay period following any directional CT. C and D: responses in altered orientation (toward S5). The neuron did not respond to any CT or during any delay period.

FIG. 6. Raw raster displays, histograms, and directional tuning of a mnemonic Oc2M neuron in normal (A and B) and altered orientations (C and D). A and B: responses in normal orientation. The neuron responded to CTs presented from direction S3, and during the delay period subsequent to S3. C and D: responses in altered orientation (toward S5). The neuron still responded to the CTs presented from S3 and S2, and during the delay period subsequent to S3. All the arrangements were identical to Fig. 5. The average response enhancement indices were 1.42 for the CT, and 1.36 for the delay. The peak response enhancement indices were 1.38 for the CT, and 1.60 for the delay period.
altered orientation. Similarly, in about one-third of neurons, the response enhancement index during the delay period was more than 1.1 for both the average (5/12 neurons) and peak responses (4/12 neurons). This indicates that the responses of these neurons during the delay period were enhanced when the rat was reoriented.

Neural responses to unfamiliar acoustic stimuli

Twelve neurons were tested by both familiar and unfamiliar CTs (familiar vs. unfamiliar acoustic stimuli). The responsiveness to CT was compared in both acoustic conditions. Of the 12 neurons, 8 neurons responded to both familiar and unfamiliar CTs (7 excitation, 1 inhibition). Three neurons responded to either familiar CT alone (1 neuron) or unfamiliar CT alone (2 neurons). One neuron neither responded to familiar nor to unfamiliar CT, but responded to the different kinds of dDNMS using cue lights. The responsiveness to the cue lights is reported separately (Nakamura et al. 1998). Thus two-thirds of neurons persisted in their responsiveness to CTs in both acoustic conditions. Tables 1C and 2B summarize these neural responses.

When the responsiveness during the delay was compared in both acoustic conditions, six neurons responded in both familiar and unfamiliar acoustic conditions. In all the neurons, the delay period responsiveness was similar (5 excited, and 1 inhibited in both acoustic conditions). During the delay period, one neuron responded only in unfamiliar acoustic conditions, and the remaining five neurons did not respond in either familiar and unfamiliar acoustic conditions. Thus many neurons maintained their responsiveness during the delay period even after unfamiliar acoustic condition.

When the neural responsiveness was summed for both familiar and unfamiliar acoustic conditions, more than one-half of the CT responsive neurons also showed significant activity during the delay period (Table 2B). Of the 11 CT responsive neurons in either or both familiar and unfamiliar acoustic conditions, 7 neurons also showed significant activity during the delay period in unfamiliar (1 neuron) or both acoustic conditions (6 neurons; Table 2B). Four CT responsive neurons did not respond during the delay period in either acoustic condition.

The typical neural responses to both familiar and unfamiliar acoustic stimuli are shown in Figs. 7 and 8. The neuron shown in Fig. 7 corresponds to a directionally discriminative neuron; unit 7 in Table 2B. The neuron responded to CTs from directions S6, S1, and S2 in the familiar acoustic condition (Fig. 7A). In the unfamiliar acoustic condition, the neuron responded to the unfamiliar CTs from S6, S1, S2, and S3 (Fig. 7B). ANOVA showed that there were no statistically significant differences between the responsiveness to the familiar and unfamiliar CTs either between two conditional comparison \(F(1,60) = 0.527, P > 0.47\) or in posthoc comparison in the respective directions \(P > 0.05\). The neuron did not respond during the delay period after either familiar or unfamiliar acoustic stimuli (Fig. 7, A and B). The neuron shown in Fig. 8 corresponds to a directional mnemonic neuron; unit 2 in Table 2B. The neuron responded to the familiar CTs from directions S1 and S2, and during the delay period subsequent to the familiar CT from S1 in the familiar acoustic condition (Fig. 8A). In the unfamiliar acoustic condition, the neuron responded to the unfamiliar CTs from S1, S2, S4, and S5, and during the delay period subsequent to unfamiliar CTs from S1, S4, and S5 (Fig. 8B). There were no statistically significant differences between the responsiveness to the familiar and unfamiliar CTs either between two conditional comparison \(F(1,59) = 0.180, P > 0.67\) or in posthoc comparison in the respective directions \(P > 0.05\). There were also no statistically significant differences between the responsiveness during subsequent delay periods either between two conditional comparison \(F(1,59) = 0.971, P > 0.32\) or in posthoc comparison in the respective directions \(P > 0.05\).

The mean numbers of the response directions of the neurons in the familiar CT condition were 1.89 ± 1.05 \((n = 9)\) for the CT and 2.00 ± 1.27 \((n = 6)\) during the delay. They were 2.80 ± 1.99 \((n = 10)\) for CT and 2.43 ± 1.81 \((n = 7)\) during the delay in the unfamiliar CT condition.

The response strength of the average and peak neural responses in familiar and unfamiliar acoustic conditions were compared, in a similar manner to the normal and reoriented conditions. For the neuron shown in Fig. 8, the average response enhancement indices were 2.06 for CT and 1.95 during the delay period. The peak response enhancement indices were 1.77 for CT and 1.20 during the delay period. The response enhancement indices for the other neurons that responded to CT (or during the delay period) in both familiar and unfamiliar acoustic conditions are shown in Fig. 9B. The response enhancement indices for CT ranged from 0.68 to 4.31 \((2.01 ± 1.43, n = 8)\) for the average response, and from 0.58 to 2.41 \((1.28 ± 0.72, n = 8)\) for the peak response. The response enhancement indices during the delay period ranged from 0.66 to 3.74 \((2.02 ± 1.29, n = 6)\) for the average response and from 0.59 to 2.50 \((1.26 ± 0.68, n = 6)\) for the peak response.

In about one-half of the neurons, the response enhancement indices to the CT were more than 1.1 for both the average responses (4/8 neurons) and peak responses (3/8 neurons). This indicates that the responses to CT of these neurons were enhanced in the unfamiliar acoustic condition. Similarly, in about two-thirds of the neurons, the response enhancement indices during the delay period were more than 1.1 for both the average response (4/6 neurons) and peak response (4/6 neurons). This indicates that the responses of these neurons during the delay period were enhanced for unfamiliar acoustic condition.

Recording sites

The approximate locations of unit recording are shown in Fig. 10. These sites were determined histologically from the small lesions made in and around the posterior parietal cortex after the end of recording. On the basis of the stereotaxic coordinates of the penetrations, the marking iron deposit and brain shrinkage, the recording sites were estimated with allowance of ±0.1 mm from the marked point. The neurons recorded were in and around the posterior parietal cortex that corresponded to Oc2M. Because there were no significant differences between the five rats, the recording sites from five rats are plotted on representative sections in Fig. 10. These neurons (128 neurons) were located in the middle of Oc2M (71 neurons; Fig. 10, B and C), near the border to Oc1M (15 neurons; Fig. 10D), and near the border to HL (42 neurons; Fig. 10A) from the atlas of Paxinos and Watson (1986). There were no
FIG. 7. Normalized mean responses of a discriminatory Oc2M neuron in both familiar (A) and unfamiliar acoustic conditions (B). A: responses in familiar acoustic condition. The neuron responded to CTs presented from directions S6, S1 and S2, but not during the delay period. B: responses in unfamiliar acoustic condition. The neuron responded to unfamiliar CTs presented from S6, S1, S2, and S3, but not during the delay period. Histograms illustrate the average neural responses to the directional CT (squares) and during the delay period (circles). The normalized activity is shown in the left vertical axis, and the actual activity in the right vertical axis. To normalize the neural activity, the mean rate during the baseline (reference) control was subtracted from the actual activity and allocated as 0.0. The mean peak responses were allocated as 1.0. Error bars represent ±1 SD. Triangle on right side: baseline activity (±1 SD) during reference period.

FIG. 8. Normalized mean responses of a mnemonic Oc2M neuron in both familiar (A) and unfamiliar acoustic conditions (B). A: responses in familiar acoustic condition. The neuron responded to CTs presented from directions S1 and S2, and during the delay period subsequent to S1. B: responses in unfamiliar acoustic condition. The neuron responded to unfamiliar CTs presented from S1, S2, S4, and S5, and during the delay periods subsequent to S1, S4, and S5. All the arrangements were identical to Fig. 7. The average response enhancement indices were 2.06 for CT and 1.95 for the delay. The peak response enhancement indices were 1.77 for CT and 1.20 for the delay. Same neuron shown in Fig. 4.
obvious differences in the neural responses of these regions. In Fig. 10, the neurons that responded to both CT and during the delay are marked by circles, and the neurons that responded to CT but not during delay are marked by triangles. The neuron number in the mark corresponds to the unit number in Table 2. The neurons that responded neither to CT nor during the delay are marked by small filled circles.

Self-stimulation behavior and stimulation sites

All five rats with posterior LHA electrodes self-stimulated. The threshold current for ICSS in the recording phase of the experiment was similar to that used in the training phase, and ranged from 30 to 200 \( \mu \text{A} \) (80 ± 75, mean ± SD, \( n = 5 \)). The stimulating electrodes that supported high rates of ICSS were in the posterior LHA, within the medial forebrain bundle (MFB), at A, −4.5 to −5.0; L, 1.4 to 1.8; V, 8.0 to 8.8 mm (Paxinos and Watson 1986).

DISCUSSION

Auditory responses of posterior parietal neurons

The posterior parietal cortex neurons coded audiospatial cues in the dDNMS task in the present study. This is not surprising because the present recorded area, Oc2M has been suggested to be polysensory in a study of evoked potential of Sprague-Dawley rats (Toldi et al. 1986). Many studies of primates have also suggested that supramodal spatial information including both visual and auditory modalities is represented in the parietal cortex (Bender and Diamond 1965; Denny-Brown et al. 1952; Farah et al. 1989; Heilman and Valenstein 1972; Hillyard et al. 1984; Mazzoni et al. 1996). It will be an important issue whether the same or different neurons within the Oc2M in the rat are responsive for visual or auditory modalities.

Directional discriminatory and directional mnemonic neurons

The present study showed that two different types of neuron (i.e., directional discriminatory and directional mnemonic neurons) exist in the Oc2M. Critically, the directional discriminatory and directional mnemonic neurons responded differently during the delay period. The directional discriminatory neurons responded only during the directional CT period. The directional mnemonic neurons responded both to directional CT and during the delay periods. Both type of neurons were intermingled and located in the same areas of the Oc2M. As for the relation of a mnemonic neural response and a behavioral licking response, the rat needed to maintain the directional information of the CT during the delay period to maximize the reward rates. Although a well-trained rat performed the task with 85% or more success, the rat occasionally mistook the trial. Also, when the rat satiated with the sucrose solution in other CT trials, the rat stopped licking. In these trials, the mnemonic responses tended to be diminished. These suggest the linkage of the mnemonic neural responses to the behavioral licking. Although the functional roles of the directional discriminatory and directional mnemonic neurons remain to be investigated, the present study clarified whether both types of neurons would retain their responsiveness in the different dDNMS conditions, i.e., in normal and altered orientations, or in familiar and unfamiliar acoustic conditions.

About three-quarters of the directional mnemonic neurons

![Diagram](http://jn.physiology.org/)

**FIG. 9.** Response enhancement indices to CT and during delay. A: comparison between normal and altered orientations. The response enhancement indices to CT were 1.27 ± 0.54 (\( n = 18 \)) for the average, and 1.23 ± 0.50 (\( n = 18 \)) for the peak responses. The response enhancement indices during the delay were 1.18 ± 0.52 (\( n = 12 \)) for the average, and 1.15 ± 0.50 (\( n = 12 \)) for the peak responses. B: comparison between familiar and unfamiliar acoustic conditions. The response enhancement indices to CT were 2.01 ± 1.43 (\( n = 8 \)) for the average, and 1.28 ± 0.72 (\( n = 8 \)) for the peak responses. The response enhancement indices during the delay were 2.02 ± 1.29 (\( n = 6 \)) for the average, and 1.26 ± 0.68 (\( n = 6 \)) for the peak responses.
did not show an altered response. These neurons responded similarly in both normal and altered orientations (12/17 neurons in Table 2A; \( P < 0.05 \), Fisher’s exact probability test), and to both familiar and unfamiliar acoustic stimuli (6/7 neurons in Table 2B; \( P < 0.02 \)). Many directional mnemonic neurons did not change their optimal response direction during either CT or the delay periods when the rat’s orientation was changed (Fig. 6) or when unfamiliar CT was used (Fig. 8). Thus these directional mnemonic neurons are related to the active mnemonic processes coding the allocentric cue locations in the experimental room. However, about one-fourth of the directional mnemonic neurons changed their responsiveness during different dDNMS conditions. These directional mnemonic neurons responded during both the CT and delay periods in at least one orientation but not in other orientations (5/17 neurons in Table 2A), or only in unfamiliar acoustic condition (1/7 neurons in Table 2B).

Among the eight directional discriminatory neurons tested in both normal and altered orientations (4 neurons in Table 2A) or in both familiar and unfamiliar acoustic conditions (4 neurons in Table 2B), one-half (4 neurons) responded to CT similarly in both normal and altered orientations (2 neurons in Table 2A), or in both familiar and unfamiliar acoustic conditions (2 neurons in Table 2B, 1 of which is shown in Fig. 7). However, the other four directional discriminatory neurons responded only to CT in either normal or altered orientations (2 neurons in Table 2A), or in either familiar or unfamiliar acoustic condition (2 neurons in Table 2B).

These results at least indicated that some directional mnemonic neurons as well as some directional discriminatory neurons retained their responsiveness under various dDNMS conditions. Thus the present results together support the concept that the posterior parietal cortex is related to the allocentric spatial information processing in both rodents and primates (Brody and Pribram 1978; Butters et al. 1972; Kesner et al. 1989, 1992; King and Corwin 1992; Kolb et al. 1994; Pohl 1973; Semmes et al. 1963).

The spatial tuning characteristics of both directional discriminatory and directional mnemonic neurons were broad; the mean number of the response directions to CT was roughly two. These cells discharged at higher rates to some CT directions and at lower rates to other CT directions. In many cells, the tuning curves were well fitted by either Gaussian curve functions, and some were fitted by sinusoidal functions of the
stimulus directions. A measure of the goodness-of-fit (coefficient of the determination, $R^2$) was calculated using both a Gaussian regression and a sinusoidal regression. The Gaussian regression described adequately the directional relations of 62% of the 50 cells ($R^2 \geq 0.7$); the fit was excellent in 28% ($R^2 \geq 0.9$), very good in 18% ($R^2 \geq 0.8$), and good in 16% ($R^2 \geq 0.7$). It was not as good in 38% of the 50 cells; the responses of these cells usually had separated double or more peaks. The sinusoidal regression adequately described the directional relations of only 28% of the 50 cells ($R^2 \geq 0.7$); the fit was excellent in 4% ($R^2 \geq 0.9$), very good in 12% ($R^2 \geq 0.8$), and good in 12% ($R^2 \geq 0.7$). Thus they fitted a Gaussian curve function of stimulus locations more favorably than a sinusoidal function (Nakamura and Takarajima 1996). This resulted in the directional tuning curves being well fitted by bell-shaped curves. Although the detailed analysis remained to be investigated, a salient finding in the present study was that individual cells did not encode the stimulus direction in a one-to-one manner. This indicates that stimulus in a particular direction is not subserved by cells uniquely related to that stimulus direction. Instead, cells with overlapping tuning curves might cooperate to recognize the stimulus location. This suggests that the spatial representation in the Oc2M is population coding (Georgopoulos et al. 1982).

The directional discriminatory and directional mnemonic neurons might also be involved in the spatial attentional control, although the response lateralization (i.e., ipsilateral or contralateral) of these neurons was not obvious in the present study. It is well-known that the parietal damaged patients have disengage deficit, a selective impairment to disengage attention from a location in the intact ipsilesional hemifield to a location in the affected contralateral hemifield (Cohen et al. 1994; Posner et al. 1984; Townsend and Courchesne 1994).

Response enhancement

In the present study, the response enhancement index of more than one-half of the directional discriminatory and directional mnemonic neurons was $>1.1$. Both the average and peak responsiveness of many directional discriminatory and directional mnemonic neurons were enhanced after the rat was reoriented or subjected to an unfamiliar acoustic condition. Because the rats were not accustomed to the altered orientation or to the unfamiliar CT, both dDNMS conditions were unfamiliar to the rats.

It is considered that the neural axis from the parietal cortex via the parahippocampal, perirhinal, and entorhinal cortical areas to the HF is important for spatial discrimination, spatial memory, and related learning. The medial temporal memory consolidation system is known to be activated by unfamiliar stimuli (Cahusac et al. 1989; Miyashita et al. 1989; Otto and Eichenbaum 1992; Rolls et al. 1989). There is a hypothesis that a frequency-dependent neural reverberation in the EC-HF loop can be initiated by increased input from the neocortex (Chrobak and Buzsaki 1994; Jones 1993). The hypothesis suggests that at high-frequency input from the neocortex to EC, the reciprocal EC-HF loop can be activated (Chrobak and Buzsaki 1994; Jones 1993). Taking this hypothesis into consideration, it is worthwhile to notice that the responses of both the directional discriminatory and directional mnemonic neurons in the Oc2M were enhanced in two unfamiliar conditions, i.e., to unfamiliar CT or in altered orientation. Because the Oc2M is the supramodal association cortex that interferes between the multimodal sensory inputs and the medial temporal memory consolidation system, it is interesting to consider that the Oc2M would have some gating role to interfere with the memory consolidation system in the medial temporal cortex.

Spatial representations in the parietal cortex

It is well-known that the response amplitude of the parietal neurons in primates is modulated by eye position (Andersen et al. 1985). The gain of the retinotopic receptive field of a cell changes with the eye position (gain modulation neuron). Turning the head and changing the eye position have similar modulatory effects on the gain modulation neuron (Brotchie et al. 1995). In rodents, turning the body is an alternative strategy for changing the eye position in primates. The responses of both directional discriminatory and direction mnemonic neurons in the present study were modulated by turning the rat and changing the body orientation. Similar gain modulation characteristics of the posterior parietal cortex in the rodents were reported in studies by Chen et al. (1994a,b). The responsiveness of directional discriminatory and directional mnemonic neurons in the present study [the HD cells and the angular motion cells (Chen et al. 1994a,b)] was considered to be modulated by vestibular or proprioceptive stimulation, i.e., by turns or body rotation.

Neurophysiological studies in primates have shown that the parietal neurons respond not only to spatial stimuli but also to the shape, size, or orientation of an object, specific type of grasping (of objects), reaching, and to eye movement (Andersen et al. 1985; Cohen and Andersen 1998; Jeannerod et al. 1995; Sakata et al. 1985). Thus the parietal cortex is involved in the spatial information processing related to many frames of reference (spatial coordinates), i.e., eye-centered, head-centered, body-centered, egocentric, angular coordinate, allocentric, object-centered, etc. Two hypotheses are now considered in the brain for these transformations (Pouget and Sejnowski 1997).

The most common is the decomposition hypothesis to a series of subtransformations, in which the object position is mapped into various intermediate frames of reference. This hypothesis predicts that different cell populations in the cortex represent the object position in the respective intermediate frame of references either by vectorial representation or by computational map (Zipser and Andersen 1988). Thus the same neuron pool represents the location of the object in a particular (only one) frame of reference.

The other is a nonlinear basis function representation hypothesis. This hypothesis predicts that the same neuron pool represents the location of the object in multiple frames of reference (Pouget and Sejnowski 1997). Based on this hypothesis, the neural network model simulated the gain-modulated cells of the monkey parietal cortex by the product of two types of nonlinear basis functions, i.e., by the product of a Gaussian function of retinal location and a sigmoid function of eye position (Pouget and Sejnowski 1997). The multiplied basis functions broadly coincided with the responses of gain-modulated cells in the parietal cortex. The model also showed that the output of such basis function...
cells could activate the cells representing various spatial frames of reference and controlling several behaviors, such as reaching and moving the eyes simultaneously (Pouget and Sejnowski 1997). Similar basis function cells had already been simulated in the hidden layer unit in Zipser and Andersen's neural network model through back-propagation learning (Zipser and Andersen 1988), although they had not elucidated the interpretation of the hidden layer unit representation. Thus, although the exact mechanisms remain to be investigated, it is reasonable to consider that multiple frames of reference are represented in the parietal cortex.

The latter hypothesis also explains why the hemineglect by lesions of the parietal cortex is not confined to a particular frame of reference (Calvanio et al. 1987; Ladavas 1987).

Similar to the gain-modulated cells in the monkey parietal cortex, the spatial tuning of both directional discriminatory and directional mnemonic neurons in the rat posterior parietal cortex were well fitted by Gaussian curve functions of stimulus locations and their responses were modulated in the condition of the altered orientation, i.e., by turning the animal. Thus the results of the present study are rather consistent with the nonlinear basis function representation hypothesis. Recently, rat posterior parietal cortex neurons were modeled by nonlinear basis functions in a spatial spreading associative neural network model that supported the latter hypothesis (Nakamura and Takarajima 1997).

The present study showed two different types of spatially tuned neurons, i.e., directional mnemonic neurons having delayed mnemonic activity and directional discriminatory neurons with no such activity, suggesting active mnemonic processes in the posterior parietal cortex of the rat.

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