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Linear Vestibular Self-Motion Signals in Monkey Medial Superior Temporal Area

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ABSTRACT: **The present study was aimed at investigating the sensitivity to linear vestibular stimulation of neurons in the medial superior temporal area (MST) of the macaque monkey. Two monkeys were moved on a parallel swing while single-unit activity was recorded. About one-half of the cells (28/51) responded in the dark either to forward motion (n = 10), or to backward motion (n = 11), or to both (n = 7). Twenty cells responding to vestibular stimulation in darkness were also tested for their responses to optic flow stimulation simulating forward and backward self-motion. Forty-five percent (9/20) of them preferred the same self-motion directions, that is, combined visual and vestibular signals in a synergistic manner. Thirty percent (6/20) of the cells were not responsive to visual stimulation alone. The remaining 25% (5/20) preferred directions that were antialigned. Our results provide strong evidence that neurons in the MST area are at least in part involved in the processing of self-motion.**

INTRODUCTION

When one is moving through a natural environment a number of sensory signals are generated that allow the nervous system to infer self-motion parameters. Many authors suggest a dominant role of cortical–visual motion areas MT and MST in the processing of visual self-motion signals.[1–3] Area MST integrates the MT output in a way that might be useful for the purpose of estimating the direction one is heading.[4] For a system involved in estimating self-motion, however, the ongoing rotational and linear head accelerations should also be taken into account. If this is true, vestibular information arising from the labyrinth organs (signaling head rotation) and from the otolith organs (signaling linear head acceleration) should also be present in area MST. Integration of head rotation signals in area MST has already been described.[5] The work reported here is the first to investigate the modulation of the responses of MST neurons during linear self-motion, that is, during linear vestibular stimulation.

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METHODS

Animal Preparation and Data Acquisition

The procedures for monkey training, electrophysiological recordings, and data analysis were described in detail in a previous paper.[6] Briefly, monkeys were surgically prepared for recordings: under general anesthesia and sterile surgical conditions, each animal was implanted with a head-holding device. Two scleral search coils were implanted in order to monitor eye position according to the method published by Judge *et al.*[7] and were connected to a plug on top of the skull. A recording chamber for microelectrode penetrations was placed in a para-sagittal plane with the recording chamber tilted 60 deg with respect to the vertical. Recording chamber, eye coil plug, and head holder were all embedded in dental acrylic, which itself was connected to the skull by self-tapping screws. Analgesics were applied postoperatively and recording started no sooner than one week after surgery. All procedures were in accordance with published guidelines on the use of animals in research (European Communities Council Directive 86/609/EEC).

During experiments, animals were seated in a primate chair with the head fixed. Behavioral paradigms and data acquisition were controlled by a PC running the NABEDA software package (Dr. Martin Pekel). Location of area MST was based on electrode and chamber position, guided by prior NMR scans and by physiological criteria.[8] MST-specific response properties that were used included large receptive fields, often extending into the ipsilateral hemifield, direction selectivity to large-field stimuli, and responses to optic-flow stimuli. While one animal is still used in experiments, histological analysis from the first monkey verified that recording sites had been located in area MST.

Experimental Setup

A parallel swing was used to move the monkey (see FIG. 1A). Monkey chair and magnetic field were placed on the swing platform. A guide rail stabilized the whole system on the ground for precise backward and forward swinging. The sinusoidal forward–backward swing movement had a frequency of 0.25 Hz. Peak-to-peak amplitude was 0.5 m, with a maximum acceleration of 1.22 m/s2. The up–down movement caused by the parallel swing mechanism had a peak-to-peak amplitude of 0.031 m and a maximum acceleration of 0.076 m/s2.

A tangent screen for presenting visual stimuli was placed in front of the animal. It covered the central 90 deg by 90 deg of the visual field when the swing was closest (0.48 m) to the screen.

Vestibular and Visual Stimuli

Pure vestibular stimulation was tested in total darkness. All room lights were shut off and the swing was separated from the remaining part of the lab with a light-tight curtain. In some sessions, the monkey had to fixate a central target that was moved together with the swing (chair-mounted LED) in order to suppress the translational vestibulo-ocular reflex (tVOR). For the optic-flow stimulation, computer-generated visual stimuli (Performer 2.1 software running on a Silicon Graphics Workstation) were back-projected by a video projector (Electrohome 4100) while the monkey had to fixate a central target. One set of stimuli was an exact virtual replica of the swing movement (see below). Another set of stimuli simulated self-motion in either the horizontal or sagittal plane in a way that allowed the testing of all possible movement directions in a single trial (see FIG. 1B). These stimuli were a

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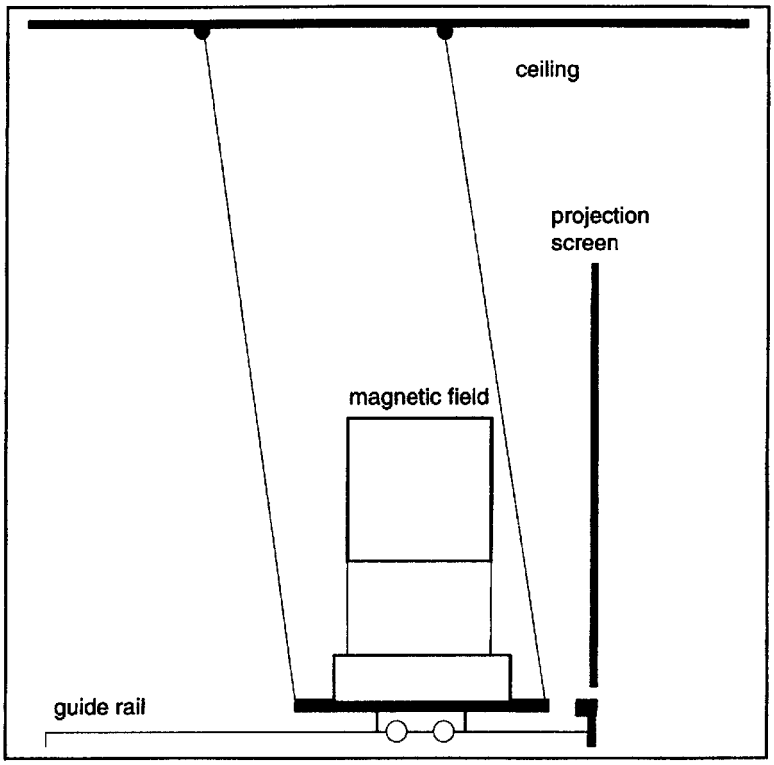

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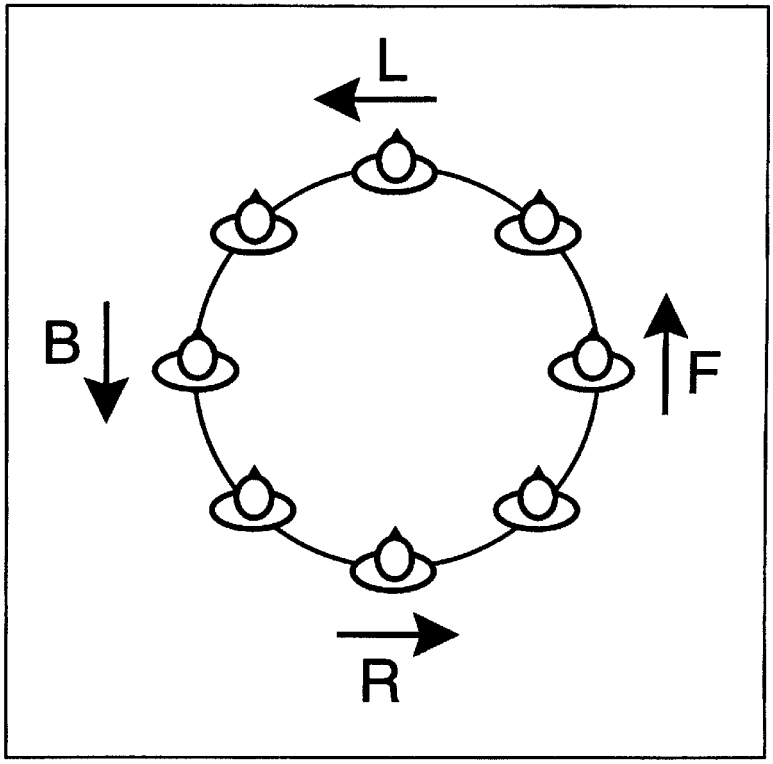

FIGURE 1. Vestibular and visual stimulation. **(A)** This panel shows schematically the experimental setup for vestibular stimulation. During the experiments, the head-fixed monkey, sitting in a primate chair, was placed on the swing with the head centered in the magnetic field. **(B)** This scheme illustrates the circular pathway paradigm for movement in the horizontal plane. The optic flow pattern presented in this case mimicked movement of an observer on the indicated trajectory in front of a large-field random-dot pattern.

three-dimensional (3-D) adaptation of a method used previously to map frontoparallel motion selectivity.[6] A detailed description can be found in that reference. Briefly, the stimulus mimicked movement through a 3-D environment on a circular path but with a constant orientation of the viewing direction. Thus, stimulus direction changed smoothly and constantly throughout the trial. These paradigms allowed determining the full 3-D directional tuning of the cells by looking at the response rate at different times during the trial.

In a subset of cells we also studied visual vestibular interactions. This was done by testing cells for their responsiveness to vestibular stimulation in darkness and in light, and comparing this to responses to pure visual stimulation that simulated the monkey's movement on the swing. In more detail, the procedure was as follows: after testing vestibular stimulation in darkness, swing movement was performed while a stationary dot pattern was presented on the tangent screen. This gave a combination of visual and vestibular stimulation. The visual stimulation consisted of expansion and contraction of the overall pattern with respect to the monkey's field of view, since the animal was moved toward and away from the tangent screen during the swing. A slight vertical motion caused by the movement characteristics of the parallel swing (see earlier) accompanied this expansion and contraction of the visual stimulus pattern. In both conditions (vestibular stimulation in darkness and visual–vestibular stimulation in light) the animal had to fixate a central target in order to suppress the tVOR. Finally, the pure visual stimulation simulated the monkeys self-motion, reproducing exactly the same pattern movement on the screen (sinusoidal expansion or contraction, accompanied by a vertical displacement) while the monkey was stationary in space.

Data Analysis

A distribution-free ANOVA was used to compare at least three different temporal intervals during the responses to vestibular stimulation. The Mann-Whitney U-test was used to test for differences between stimulus-driven activity and spontaneous activity in the visual paradigm.

RESULTS

Fifty-one neurons from two hemispheres of two macaque monkeys were tested for their responsiveness to linear vestibular stimulation. Twenty-eight neurons (55%) showed a statistically significant response ($p<0.05$). An example is shown in FIGURE 2. The histogram in the upper panel reveals clearly that this cell preferred forward movement over backward movement in total darkness ($p<0.0001$). The lower panel indicates the position of the swing during the trial.

The very same cell was also tested for its responsiveness to visual stimulation using optic flow fields that simulated self-motion (FIG. 3). The left column of this figure shows the result for stimulation in the horizontal plane, as histogram (upper panel) and as polar plot (lower panel). As already described in the Methods section, this stimulation method simulated a self-motion in which the movement direction changed continuously (circular

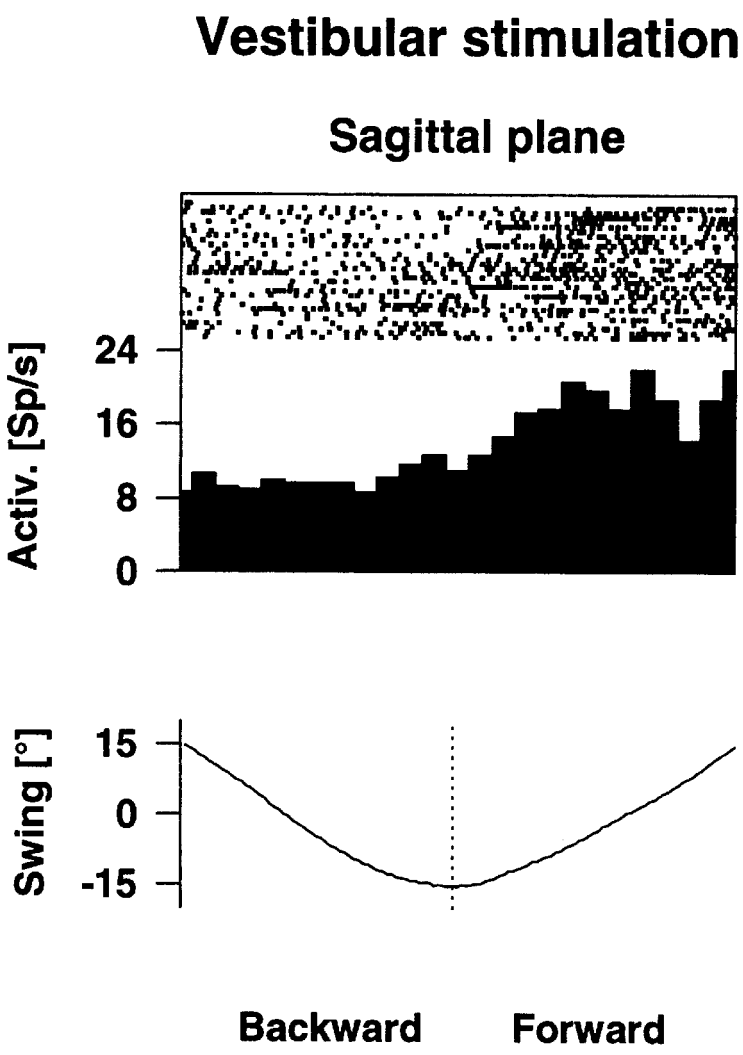

FIGURE 2. Response of a MST neuron to vestibular stimulation in darkness. The histogram indicates the firing rate of the neuron during sinusoidal backward and forward motion. The lower panel indicates the position of the parallel swing during the trial.

pathway stimulation). The right column shows the result of testing the cell with circular pathway stimulation in the sagittal plane, again as histogram (upper panel) and as polar plot (lower panel). It is very obvious from both stimulations that this cell preferred exclusively forward motion, that is, an expansion stimulus. Thus, for this neuron the preferred self-motion directions for visual and vestibular stimulation were equally directed in space.

Fifty-five percent of the cells (28/51) revealed a significant response to linear vestibular stimulation. This result was obtained regardless of whether or not the animal had to suppress the tVOR by fixating a chair-mounted LED. As shown in FIG. 4, 10 (36%) cells preferred forward motion, while 11 (39%) cells preferred backward motion. Seven (25%) cells showed a bidirectional response characteristic. Twenty cells that were responsive to real physical movement in darkness were also tested for their response to visually simulated self-motion. As shown in FIGURE 5, almost half of the cells (9/20) preferred the same direction of self-motion in space in both conditions (pure visual and pure vestibular stimulation) and therefore were synergistically organized. Five (25%) cells had different preferred directions for visual and vestibular stimulation and thus were nonsynergistically organized, while 6 (30%) cells were not responsive to visual stimulation.

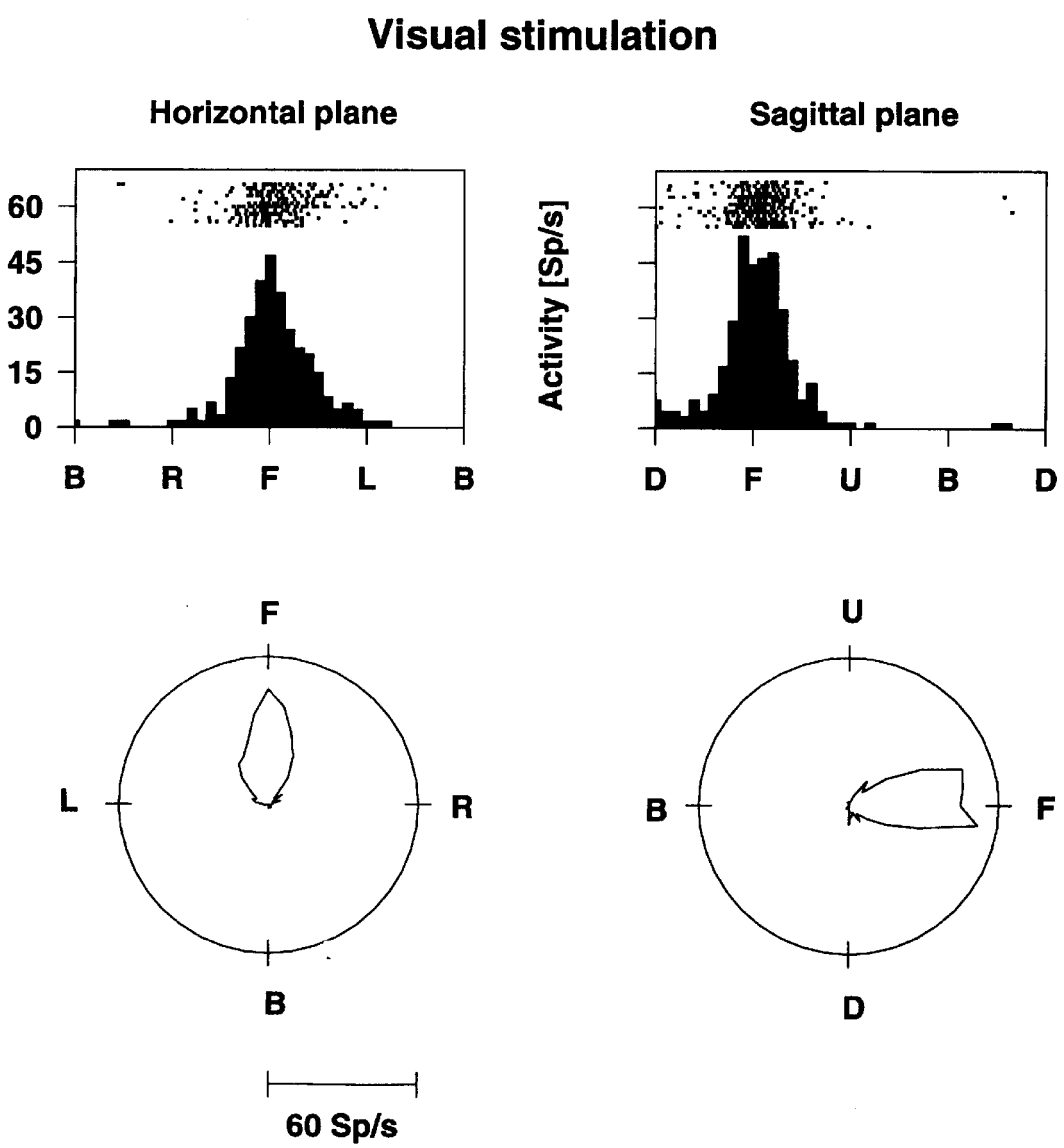

FIGURE 3. Response of the very same neuron to visual stimulation. The left and right columns show the response of the neuron from FIGURE 2 to optic flow fields simulating self-motion. The **left column** indicates the responses for simulated movement in the horizontal plane. The **right column** shows responses for simulated movement in the sagittal plane. Movement directions changed continuously throughout the trial in both stimulus conditions. Movement directions indicated specifically: F = forward; L = left; B = backward; R = rightward; U = upward; D = downward.

Finally, a small subset of cells (n = 11) was tested completely for visual-vestibular interactions, that is, neuronal activity was recorded for vestibular stimulation in darkness and in light as well as for pure visual stimulation. The visual stimulation used in this case exactly mimicked the swing movement, while the monkey was stationary in space. An even more complex response pattern emerged from these experiments. Only a few of the cells preferred the same self-motion directions in space in all three experimental conditions. Others had the same response characteristic for vestibular stimulation in darkness and light, while visual stimulation could not drive the cell or caused a different response profile. Finally, we found cells that did not respond to pure visual or vestibular stimulation alone, but only for a combined visual vestibular stimulation. Yet, the small number of neurons recorded does not allow any population analysis.

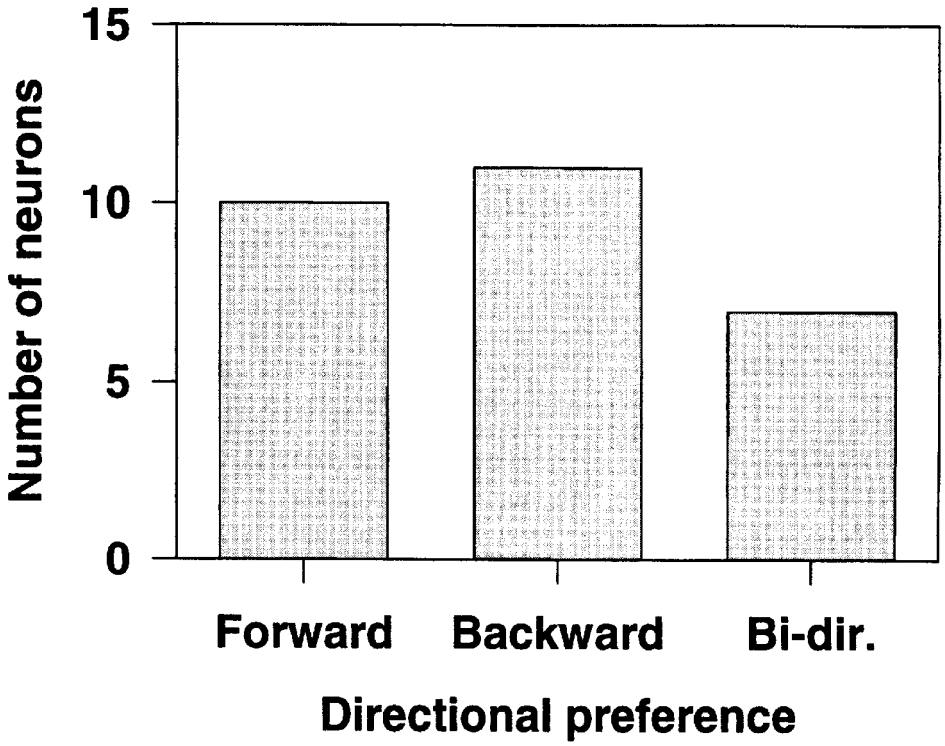

FIGURE 4. Distribution of preferred directions for vestibular stimulation. The bars in this histogram indicate the numbers of neurons being responsive for forward movement, backward movement, or movement into both directions (bi-dir.).

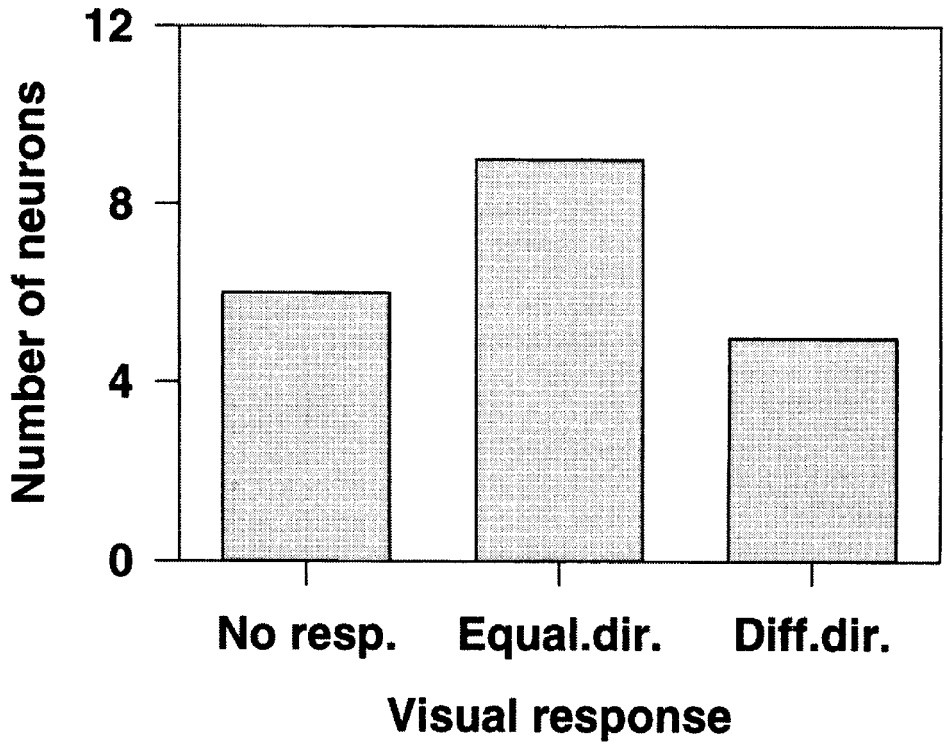

FIGURE 5. Distribution of visual vestibular interactions. The bars in this histogram indicate the number of vestibular responsive neurons in which the preferred direction for visual stimulation were either in the same (*middle bar*) or in the opposite (*right bar*) direction of the vestibular preferred direction. Some of the vestibular responsive neurons had no significant visual response (*left bar*).

DISCUSSION

Response to Linear Vestibular Stimulation

Our results show that MST neurons respond to linear vestibular stimulation. Seventy-five percent of the vestibular responsive cells responded selectively to only one movement direction (forward or backward), while the remaining cells had a bidirectional response profile. Almost half of the vestibular responsive cells (45%) preferred the same self-motion direction in space when simulated by optic flow fields. However, the remaining 55% of the cells responded either for the opposite direction or were not responsive to visual stimulation. This indication of cross-modal interactions was confirmed in a study on a subset of cells that was tested for vestibular stimulation in darkness and light as well as for pure visual stimulation. Thus, from our experiments it can be concluded that visual vestibular interactions take place in the MST area and that both sensory signals are not always combined in a synergistic manner. Instead, for about half of the cells visual response characteristics seemed to be independent of vestibular responsiveness.

Vestibular Signals in the Cortex

Responses to vestibular stimulation have already been described for several cortical areas in the macaque. It was first found in area 2v adjacent to the somatosensory face field. Subsequently, vestibular responsiveness was found in area 3a within the somatosensory arm field, in the PIVC region, area 7, MST area, VIP area, area T3, and also the FEF.[9–15] Most neurons in these areas respond to head velocity and receive converging visual, vestibular, and somatosensory input. Interestingly, all neurons in the VIP area as well as many neurons in the other cortical areas reveal a nonsynergistic behavior in that their preferred directions for visual and vestibular stimulation are coaligned.[12,13] The functional role of this preference for these nonsynergistic stimuli is not clear.

It is not only the dynamic context of head *rotation* that is represented in these cortical areas. It was also shown before that the angular head *position* in space influences the activity of parietal cortex neurons.[16] For many of these neurons head and eye position influenced neuronal activity in a synergistic manner, that is, neuronal activity was, for example, increased by having the eyes or the head (or both) in an eccentric position relative to the straight-ahead direction of the trunk.

To our knowledge, however, all studies on vestibular responsiveness so far involved exclusively rotational components thereby stimulating the semicircular canals. The representation of linear vestibular signals from the otoliths has not been shown yet. Our results therefore show for the first time responsiveness of the macaque cortical system to linear vestibular stimulation. Moreover, this responsiveness is located in an area that has been associated with the processing of self-motion based on its optic flow response properties.[1–4]

The Functional Role of Vestibular Signals in the Cortex

The functional role of cortical vestibular responsiveness is best understood by results coming from lesion studies. Several studies have shown that lesions of the parietovestibular regions influence the VOR.[17] Often an asymmetry in the VOR is observed, with a lower gain of the slow phases directed to the ipsiversive side, and sometimes a lesion in this cortical area leads to a spontaneous nystagmus away from the lesioned side. Lesions of the identified vestibular areas can modify normal cognitive behavior like locomotor navigation or the percept of visual spatial constancy. Straube and Brandt[18] could show that a

patient with lesions of the vestibular cortex did not have the impression of vection when visual stimulation was restricted to the ipsilateral part of the visual field with respect to the lesion side. In addition, vestibular signals can also be used for spatial memory processes in humans[19,20] such as path integration.

SUMMARY

Our results show that many neurons in the MST area are activated during real self-motion, which generates linear vestibular signals arising from the otoliths. About the same number of cells responded to either forward or backward motion. About half of the vestibular responsive cells responded to visual stimuli simulating self-motion in a synergistic manner. The hypothesis that the MST area is involved in the processing of self-motion information is supported by our present findings. These results point toward a sensory-integrating rather than a purely visual function of the MST area.

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