Electrical Microstimulation of the Fastigial Oculomotor Region in the Head-Unrestrained Monkey

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1Unité 534, Institut National de la Santé et de la Recherche Médicale/Université Claude Bernard-Lyon 1, IFR 19 Institut Fédératif des Neurosciences de Lyon, Bron; and 2Institut de Neurosciences Cognitives de la Méditerranée, UMR 6193, Centre National de la Recherche Scientifique, Aix-Marseille Universités, Marseille, France

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Quinet J, Goffart L. Electrical microstimulation of the fastigial oculomotor region in the head-unrestrained monkey. J Neurophysiol 102: 320–336, 2009. First published May 13, 2009; doi:10.1152/jn.90716.2008. It has been shown that inactivation of the caudal fastigial nucleus (cFN) by local injection of muscimol leads to inaccurate gaze shifts in the head-unrestrained monkey and that the gaze dysmetria is primarily due to changes in the horizontal amplitude of eye saccades in the orbit. Moreover, changes in the relationship between amplitude and duration are observed for only the eye saccades and not for the head movements. These results suggest that the cFN output primarily influences a neural network involved in moving the eyes in the orbit. The present study further tested this hypothesis by examining whether head movements could be evoked by electrical microstimulation of the saccade-related region in the cFN. Long stimulation trains (200–300 ms) evoked staircase gaze shifts that were ipsi- or contralateral, depending on the stimulated site. These gaze shifts were small in amplitude and were essentially accomplished by saccadic movements of the eyes. Head movements were observed in some sites but their amplitudes were very small (mean = 2.4°). The occurrence of head movements and their amplitude were not enhanced by increasing stimulation frequency or intensity. In several cases, electrically evoked gaze shifts exhibited an eye-head coupling that was different from that observed in visually triggered gaze shifts. This study provides additional observations suggesting that the saccade-related region in the cFN modulates the generation of eye movements and that the deep cerebellar output region involved in influencing head movements is located elsewhere.

INTRODUCTION

When a visual target suddenly appears in the visual field, a saccadic movement of both eyes is generated, sometimes accompanied with a head movement, to rapidly shift the two lines of sight toward the target location (Collewijn et al. 1997). The medio-posterior cerebellum (MPC), composed of the oculomotor vermis (lobules VIc and VII) and the two caudal fastigial nuclei, is a major structure for controlling the accuracy of gaze shifts (see Pélikson et al. 2003a; Robinson and Fuchs 2001 for reviews). The two caudal fastigial nuclei, also known as the fastigial oculomotor regions, (Ohtsuka and Noda 1990) generate the main output by which the MPC influences the brain stem circuits that are involved in the generation of saccades. A subset of neurons in the MPC generates a burst of action potentials during saccades, irrespective of saccade direction and amplitude (Fuchs et al. 1993; Helmchen and Büttner 1995; Helmchen et al. 1994; Kleine et al. 2003; Llinas and Wolfe 1977; Ohtsuka and Noda 1991, 1995). In the head-restrained monkey, unilateral inactivation of the caudal fastigial nucleus (cFN) by local injection of muscimol severely impairs the accuracy of visually triggered saccades: the horizontal amplitude is hypermetric for ipsilesional saccades and hypometric for contralesional saccades, while vertical saccades are deviated toward the injected side with a magnitude that increases with target eccentricity (Goffart et al. 2004; Iwamoto and Yoshida 2002). In the head-unrestrained monkey, cFN inactivation also leads to dysmetric gaze shifts. For ipsi- and contralesional horizontal gaze movements, the dysmetria is primarily due to dysmetric saccades of the eyes in the orbit, uncompensated by appropriate changes in the head contribution. Moreover, changes in the relationship between amplitude and duration are observed only for eye saccades but not head movements (Quinet and Goffart 2005, 2007a). These observations suggest that the cFN output essentially influences an oculomotor mechanism that is functionally situated beyond the location where gaze-related signals have split into two distinct premotor commands: one for moving the eyes in the orbit and one for moving the head. If this hypothesis is correct, electrical microstimulation of cFN output should evoke saccadic eye movements and fail to elicit movements of the head.

Previous investigations in the head-restrained monkey have shown that electrical microstimulation of the oculomotor vermis (lobules VIc-VII) elicited ipsilateral eye saccades (Fujikado and Noda 1987; Noda and Fujikado 1987a,b). Microstimulation of the fastigial nucleus also elicits saccadic eye movements (Cogdell et al. 1977; Noda et al. 1988; Ron and Robinson 1973). Ipsilateral saccades are elicited by stimulating the dorsocaudal portion, whereas contralateral saccades are evoked by stimulating the ventromedial region of the fastigial nucleus. Local injection of bicuculline in the fastigial nucleus suppresses the elicitation of ipsilateral saccades (Noda et al. 1988; Sato and Noda 1992a). Based on these observations, ipsilateral saccades are thought to be produced by stimulating the afferent axons of Purkinje cells from the oculomotor vermis; whereas contralateral saccades are produced by activating the efferent axons of cFN neurons en route toward the saccade generator in the contralateral ponto-medullary reticular formation (see also Sato and Noda 1991).

Very few studies have examined the effect of microstimulating the fastigial nucleus or the posterior vermis in the head-unrestrained monkey. Mussen (1930) reported: “when the lobus medius of the vermis is stimulated, the head turns toward the side excited through the action of the opposite sternomas-
Microstimulation of CFN in the head-unrestrained monkey

**Methods and surgical procedures**

Two adult rhesus monkeys (B: 8.8 kg and E: 5.7 kg) were used for this experiment. Two surgical procedures under isoflurane anesthesia and aseptic conditions were performed. First, a light titanium head post (7 g), used for the immobilization of the head, was secured on the top front center of the skull using stainless steel screws and bone cement (Palacos, Smith and Nephew). Eye movements were monitored using a three-turn magnetic search coil that was sutured with silk to the sclera of one eye. Search coil wires were passed under the skin and fixed to a connector located on the top of the skull. Head movements were monitored using a similar coil that was glued to a piece of plastic and fixed to the skull with bone cement. Training on the behavioral tasks (first with the head restrained and then with the head unrestrained) was performed after full recovery. In the second surgical procedure, a craniotomy was performed on the skull, and a recording chamber was stereotaxically placed for stimulating the caudal part of the fastigial nucleus. The chamber was placed in the frontal plane, stereotaxically centered on the midline between the two fastigial nuclei (9 mm posterior and 7 mm above the interaural line), and tilted 20° to the right with respect to the sagittal plane. All surgical procedures and experiments were performed in accordance with the guidelines from the French Ministry of Agriculture (87/848) and from the European Community (86/609/EEC).

**Behavioral task**

Animals were seated in a primate chair that prevented rotations of the trunk without restraining movements of the head. The primate chair was fitted with foam cushions (front and back) that gently but firmly positioned the trunk of the animal in front of the target display. The monkey's head was free to move in all three dimensions without restriction over a range of approximately -70 to 70°. Gaze and head movements were measured with a phase angle detection system (CNC Engineering, 3-A coil frame). Two phase detectors were used to independently record gaze and head angular deviations (hereafter called positions). Gaze position signals were calibrated by having the head-unrestrained animal fixate stationary targets that were placed ±20° horizontally or vertically. The head coil was calibrated at the site where the magnetic field was oriented to the right with respect to the sagittal plane. All surgical procedures, a craniotomy was performed on the skull, and a recording chamber was stereotaxically placed for stimulating the caudal part of the fastigial nucleus. The chamber was placed in the frontal plane, stereotaxically centered on the midline between the two fastigial nuclei (9 mm posterior and 7 mm above the interaural line), and tilted 20° to the right with respect to the sagittal plane. All surgical procedures and experiments were performed in accordance with the guidelines from the French Ministry of Agriculture (87/848) and from the European Community (86/609/EEC).

**Data analysis**

A total of 25 sites were tested with electrical microstimulation in the head-unrestrained condition (monkey B: 17 sites, monkey E: 8 sites). For the sake of simplicity, reproducibility, and consistency, we only describe the first movements that were evoked with the same
stimulation parameters across all the sites (400–600 Hz, 100–300 ms and 1–3 T). They concern 22 sites in the fastigial nucleus of two monkeys (15 sites for monkey B and 7 sites for monkey E). The data were digitized on-line and analyzed off-line using a software program that detected the onset and offset of saccades and head movements on the basis of a velocity threshold (15°/s). The results of the automatic detection were checked by inspecting each trial individually and adjusted manually when necessary. Trials where a movement of the head was initiated before the onset of the stimulation train (head velocity exceeding 15°/s) were excluded from the analysis. Several parameters such as amplitude, duration, and peak velocity of each detected horizontal and vertical gaze and head movements were measured automatically. To facilitate the reading of results and figures, horizontal amplitude was expressed so that positive values correspond to ipsilateral movements and negative values to contralateral movements. Positive values of vertical amplitude correspond to upward movements, negative values to downward movements.

Localization of stimulation sites

After termination of all experiments (unit recording studies, microstimulation, and pharmacological local injections), one animal (monkey B) was killed by an overdose of pentobarbital sodium and perfused transcardially with saline, followed by 10% formalin. Standard techniques were used to prepare slices of 60 μm thickness on a freezing microtome. The observation of electrode tracks in coronal sections confirmed that our electrode penetrations were all made in the fastigial oculomotor regions: 1) the recording of saccade-related units at about the same depths (saccade-related neurons in the interpositus nucleus are located much more ventrally), 2) the reversal in gaze amplitude was not related to a variability in initial horizontal position corresponding to angular deviation of the eyes toward the side contralateral to the stimulation site. Top: horizontal component; bottom: vertical component. Stimulated sites: site b7 (A and B) and site e8 (C and D). Stimulation parameters: 200 ms, 400 Hz, and 2 times the threshold current for evoking saccades in the head-restrained monkey.

RESULTS

Depending on the site of stimulation, electrical stimulation elicited either contra- or ipsilateral movements. Of particular interest to us, we start the results by describing the contralateral movements. As shown by Noda et al. (1988) and in agreement with the efferent projections of FOR neurons toward the contralateral reticular formation (Batton et al. 1977; Noda et al. 1990), contralateral movements result from the recruitment of the axons (i.e., the output) of FOR neurons. The description of ipsilateral movements follows but not as extensively as contralateral movements because their study should be complemented by further stimulation studies in the posterior vermis. Because it is known that axons from the posterior vermis converge toward the caudal end of the fastigial nucleus, it is possible that ipsilateral movements result from stimulating Purkinje cells axons which do not belong to the oculomotor vermis (e.g., lobules VIII) (Sato and Noda 1992b).

Contralateral movements

Figure 1 illustrates the time course of typical contralateral gaze (A and C) and head (B and D) movements evoked by electrical microstimulation in the left cFN (stimulation parameters indicated in the legend). Site e8 (C and D) was a site where saccade-related units were found, whereas site b7 (A and B) was located about 1.4 mm rostral to the saccade-related region. For each site, microstimulation evoked staircase gaze saccades with a latency range of 20–54 ms (site b7) and 20–24 ms (site e8) after stimulation onset. The amplitude of the first evoked gaze shifts could be quite variable. For site b7, the gaze displacement had a horizontal amplitude (top) ranging from −2.1 to −5.6° and a vertical amplitude (bottom) ranging from 2.6 to 6.1°. For site e8, the horizontal amplitude ranged from −5.3 to −13.9° and the vertical amplitude from 0.9 to 2.6°. The horizontal amplitude of gaze shifts evoked at site e8 was more variable than the vertical amplitude. The variability in horizontal gaze amplitude was not related to a variability in initial horizontal head position (ranging from −6.7 to 16.1° for site b7.
and from $-10.3$ to $8.3^\circ$ for site e8) because no significant correlation was found between the two parameters (Pearson correlation coefficients $R = 0.29$ and 0.05; $P$ values = 0.38 and 0.87, for sites b7 and e8, respectively). The larger variability in amplitude did not always involve the horizontal component because the amplitude of the vertical component was more variable at other sites (e.g., b8). The observed eye movements always preceded the onset of head movements. The delay between the onsets of the first eye and head movements (eye-head delay) was also variable, ranging from 4 to 46 ms for site b7 and from 48 to 90 ms for site e8. When a head movement was evoked (in 9 of 11 stimulation trials for site b7 and in 10 of 12 trials for site e8), its direction was mostly horizontal. The horizontal amplitude of head movements did not exceed $-4.2^\circ$ for site b7 and $-8.5^\circ$ for site e8, whereas the vertical amplitude ranged from $-2.2$ to $2.6^\circ$ for site b7 and from $-1.0$ to $1.0^\circ$ for site e8.

Figure 2 shows the average horizontal and vertical amplitudes (error bar = 1 SD) of the first gaze (A) and head (B) movements evoked when a 400 Hz stimulation train was used (current = 2 times the threshold for evoking saccades in the head-restrained condition except for site b1 where current = 1.5 T). Across all stimulated sites, the average horizontal gaze amplitude ranged from $-3.7^\circ$ (site b7) to $-25.7^\circ$ (b11) in monkey B and from $-4.7^\circ$ (e3) to $-9.1^\circ$ (e8) in monkey E, whereas the average vertical gaze amplitude ranged from $2.4^\circ$ (b12) to $9.6^\circ$ (b11) and from $0.8^\circ$ (e6) to $1.6^\circ$ (e8) for monkeys B and E, respectively. We did not find any topographical organization in the explored sites (e.g., along the mediolateral, rostrocaudal, or dorsoventral extents) that would account for the variability in the amplitude and direction of contralateral movements.

At most sites (66%), the observed head movements were very small in amplitude ($<1^\circ$) despite the fact that high frequencies (400–600 Hz) and long (200 ms) stimulation trains were tested. In monkey B, the average horizontal amplitude of contralateral head movements ranged from $-0.2$ (b8) to $-7.0^\circ$ (b11) and the average vertical amplitude from $-1.4$ (b11) to $2.0^\circ$ (b13). In monkey E, the average horizontal amplitude ranged from $-0.7$ (e4) to $-3.0^\circ$ (e8) and the vertical amplitude ranged from 0.0 (upward deviation, e4 and e6) to $-0.1^\circ$ (downward deviation, e8).

Table 1 provides the average horizontal amplitude of gaze shifts, eye saccades, and head movements, the percentage of trials where a head movement was detected, the average latency of evoked movements (gaze and head), and the average delay between the onsets of the eye and head movements (eye-head delay). The average amplitude of eye saccades ranged from $-3.6$ to $-24.2^\circ$, whereas that of head movements ranged from $-0.2$ to $-7.0^\circ$. No significant correlation was found between the mean eye amplitude values and the mean head amplitude values. The variability in amplitudes observed across sites was also not related to the number of evoked movements because no significant correlation was found between the SD values and the number of evoked movements. Moreover, for each site taken separately, there was no correlation between horizontal eye saccade amplitudes and starting head positions, even when the range of the latter was relatively large (e.g., from $-12.7$ to $11.9^\circ$ in site b8). Interestingly, significant correlations were found between the mean (X) and standard error [SD/sqrt(N), Y] values, for the eye saccade amplitudes [Bravais-Pearson correlation coefficient $R(X,Y) = 0.74$, $P < 0.001$, $n = 17$] as well as for the head movement amplitudes [$R(X,Y) = 0.76$, $P < 0.001$]. In other words, the electrically evoked movement amplitudes were more variable for the sites where larger movements were elicited.

In 55% of sites, head movements were not observed to accompany electrically evoked eye saccades (Table 1). Such a failure to systematically elicit a head movement was observed for six sites in monkey B and for all sites in monkey E. The inconsistent observation of head movements was made at sites associated with either small head movements (e.g., sites b8, b12, and e4) or at sites associated with relatively larger head...
movements (e.g., sites b11, b14, and e8). The absence of head movement was not due to any particular positions of the head at the time of stimulation. For sites where the head did not move for at least three trials (sites b8, b11, b12, e3, and e6), no significant difference in horizontal or vertical initial head position was found between gaze shifts associated with head movements and those without head movements (Mann Whitney U test, \( P > 0.05 \)). Concerning the latency of gaze shifts, the average value ranged from 20 (b5) to 88 ms (b10) in monkey B and from 21 (e8) to 69 ms (e4) in monkey E, whereas the average latency of head movements ranged from 46 (b17) to 154 ms (b2) and from 75 (e6) to 92 ms (e4). The eye-head delay of contralateral movements ranged from 11 ± 14 ms (b17) to 88 ± 29 ms (b2) and from 12 ± 10 ms (e6) to 70 ± 17 ms (e8) for monkeys B and E, respectively.

The relationship between the amplitude of gaze shifts and the amplitude of their ocular component was analyzed to further illustrate that the evoked gaze shifts were mainly due to saccadic eye movements. Figure 3 shows the relationship obtained for three sites (b11, b12, and e6). For both horizontal (left) and vertical (right) components of gaze shifts, the amplitude of the eye component increased linearly with increasing gaze amplitude. With slopes close to unity (horizontal component: 0.95, 1.0, and 0.96, vertical component: 0.97, 1.0, and 1.04 for b11, b12, and e6, respectively) and near zero y

### Table 1

Summary data for 22 stimulation sites in two monkeys. For each site, the direction (ipsi- or contralateral) of evoked movements, the number of stimulation trials and the mean ± SD of horizontal amplitude of gaze shifts, eye saccades, and head movements are given. Latencies of gaze and head movements and eye-head delays are also documented. Because stimulation did not consistently evoke a head movement (see text), the percentage of evoked head movements is indicated. All movements were evoked with current \( \geq \) two times the threshold of current intensity except for site b1 (1.5 times the threshold). In some sites (e.g., b8, b10, and b11), several trials (~40%) were excluded from the analysis because the head moved before the onset of the stimulation train, resulting in only a small number of analyzed trials (see METHODS).

### Controlal movements

![Graph showing the contribution of the eye to the amplitude of gaze shifts evoked at 3 sites. The relationship between the amplitude of the eye component and the amplitude of contralateral gaze shifts for both horizontal (left) and vertical (right) components. Stimulation parameters: 200 ms, 400 Hz, and current = twice the threshold for evoking saccades in the head-restrained monkey.](https://www.jn.org)}}
intercepts (horizontal component: −0.47, −0.04, and 0.04, vertical component: 0.69, −0.04, and 0.00), the relationship indicates that the gaze displacements were mostly performed by the eyes. Table 2 provides the regression parameters (slopes, y intercepts, and $R^2$) obtained for all sites. Focusing on the horizontal component, the slopes ranged from 0.77 to 1.07, the y intercepts ranged from −0.47 to 1.39, and the variance accounted for by the linear regression ($R^2$ values) ranged from 72 to 100%. Concerning the vertical component, the slopes values ranged from 0.87 to 1.09, the y intercepts ranged from −0.48 to 0.75, and the $R^2$ values ranged from 86% to 100%. Furthermore, when the horizontal amplitudes of gaze shifts were compared with those of their saccadic ocular components, statistically significant differences were found for seven sites in monkey B and one site in monkey E (Wilcoxon test, P < 0.05). However, the average differences in amplitude between horizontal gaze and gaze amplitudes (which correspond to the amplitudes of the head contribution to the horizontal amplitude of gaze shifts) were small and ranged from $−0.5 \pm 0.3^\circ$ (site b16) to $1.5 \pm 1.6^\circ$ (site b11). For the vertical component, the gaze amplitude was significantly different from the eye amplitude in only two sites (b2 and b14).

The observed head movements had small amplitudes and rather long latencies. This might suggest that the FOR activity participates in the generation of small amplitude gaze shifts. Indeed, small visual gaze shifts in the monkey are known to exhibit a minor head contribution and long eye-head delays (Freedman and Sparks 1997; Phillips et al. 1995; Tomlinson and Bahra 1986). To address this question, we compared the eye amplitude between stimulation-evoked and visually triggered movements that were matched in amplitudes and starting positions of the gaze and head. For each stimulation site, Table 3 contains the average values of horizontal gaze and eye amplitude and the mean eye-head delay for stimulation-evoked movements (column stimulation) and visually triggered gaze shifts (column visual). Statistically significant differences (Mann-Whitney U test) in eye amplitude were found in 26% (n = 4) of the sites (smaller eye amplitude for electrically evoked movements, average difference = 1.4 ± 0.5°), whereas the eye-head delay was significantly different in 46% (n = 7) of the sites (longer delay of head movement onset, average difference = 41 ± 23 ms).

Increasing stimulation frequency did not increase the probability of observing a movement of the head. For 10 sites tested with matched stimulation current (7 sites in monkey B and 3 sites in monkey E), increasing the frequency from 400 to 600 Hz did not significantly increase the probability of observing a head movement ($\chi^2$ test, P > 0.05). When examining the effect of increasing the frequency within each site, the horizontal amplitude of head movements was slightly increased in only three sites (average increases = 1.8, 3.3, and 5.4° for sites b5, b17, and e8, respectively), whereas the vertical head amplitude did not change. The latency of head movements was significantly changed at site b17 (86% increase) and site e6 (28% decrease), but the paired comparison did not reveal any significant change in head movement latency between 400 and 600 Hz (average difference = −1.0 ± 18 ms; P = 0.96).

In addition, increasing stimulation current intensity did not increase the probability of observing head movements either. In six sites tested with matched stimulation frequency (4 sites in monkey B and 2 sites in monkey E), increasing stimulation current from 2 to 3 T did not significantly increase the occurrence of head movements ($\chi^2$ test, P > 0.05). The horizontal amplitude of head movements was increased with increased current intensity in three of six sites (average increases = 2.5, 3.3, and 4.1°).
2.7, and 2.9° for sites b7, b17, and e4, respectively). For head latency, a statistically significant increase was observed in two of six sites (average difference = 23 and 21 ms for sites b7 and b17, respectively), but the paired comparison between both current intensities revealed no statistically significant change in head latency (average difference = −1 ± 21 ms; P value = 0.89).

Releasing the monkey's head did not significantly change the amplitude or latency of electrically evoked gaze shifts. The horizontal and vertical gaze amplitudes were not significantly different between head-restrained and head-unrestrained conditions (Wilcoxon test; average differences in horizontal and vertical amplitude = −0.6 ± 3.8 and 0.3 ± 4.7° in monkey B, −0.4 ± 0.8 and 1.0 ± 1.0 in monkey E). In the same vein, gaze latencies were not different between the two conditions (average difference = 2 ± 8 and 8 ± 10 ms for monkeys B and E, respectively).

Interestingly, in some sites (e3 and b14), a mismatch between the direction of an electrically evoked gaze shift and the direction of the accompanying head movement was observed (see examples in Figs. 4, C, and F). At site e3 (200 ms, 600 Hz, 3 T) on average, gaze shifts were directed to the left (−7.0 ± 1.2°) with a slight upward component (1.1 ± 1.1°), whereas the head moved to the right (1.5 ± 0.5°) with a slight downward component (−0.9 ± 0.7°). At site b14 (200 ms, 600 Hz, 2.5 T), gaze and head movements both moved to the left (−9.0 ± 1.0 and −6.3 ± 2.9°, respectively). However, while the gaze moved upward (2.3 ± 0.8°), the head moved downward (−3.1 ± 1.6°).

The velocity of electrically evoked eye and head components of gaze shifts were bell-shaped. For sites b7 (A) and e8 (B), the directions of both eye saccades and head movements were comparable. For site e3, both movements had different horizontal directions: eye saccades were directed to the left and the head moved to the right (as a result, gaze moved to the left). Note also that the velocity of the vertical eye component was not bell-shaped (the trajectory of evoked saccades were curved). Horizontal and vertical gaze velocities were variable in spite of constant stimulation parameters (i.e., 200 ms, 400 Hz, and 2 T for sites b7 and e8; 200 ms, 600 Hz, and 3 T for e3). The horizontal peak velocity of the first saccadic eye movement ranged from 103 to 247°/s (b7), 262 to 448°/s (e8), and 308 to 498°/s (e3), whereas the vertical peak velocity ranged from 137 to 255°/s, from 57 to 145°/s, and from 79 to 135°/s (for sites b7, e8, and e3, respectively). Concerning head movements, the horizontal peak velocity of the first detected movement ranged from 4 to 26°/s (b7, movements evoked in 82% of trials), 7 to 63°/s (e8, movements evoked in 91% of trials), and 14 to 39°/s (e3, movements evoked in 100% of trials), whereas the vertical velocity ranged from 3 to 30°/s, from 6 to 25°/s, and from 8 to 21°/s, respectively.

For all three sites, a significant correlation was found between horizontal peak velocities and amplitudes of electrically evoked gaze shifts (R = 0.91, R = 0.90, and R = −0.89 for site b7, e8, and e3, respectively). Statistically significant correlations were found in 8 of 11 sites in monkey B [R ranging from 0.61 (b13) to 0.96 (b1)] and in all sites in monkey E [R ranging from 0.90 (e3 and e8) to 0.96 (e6)]. Significant correlations were also found between gaze duration and gaze amplitude for 6 of 11 sites in monkey B and for all sites in monkey E [R ranged from 0.78 (b12) to 0.91 (b1) and from 0.80 (e3) to 0.97 (e6) for monkeys B and E, respectively]. The dependency between eye and head movements was tested for each site by analyzing the correlation between their horizontal peak veloc-

**TABLE 3.**

<table>
<thead>
<tr>
<th>Site</th>
<th>Direction</th>
<th>Parameters (ms, Hz, T)</th>
<th>Gaze Amplitude,°</th>
<th>Eye Amplitude,°</th>
<th>Eye-Head Delay, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1</td>
<td>Contra</td>
<td>200 400 1.5</td>
<td>−6.4 ± 7.6 (10)</td>
<td>−7.4 ± 3.1 (20)</td>
<td>NS</td>
</tr>
<tr>
<td>b2</td>
<td>Contra</td>
<td>300 400 2</td>
<td>−4.5 ± 1.4 (9)</td>
<td>−4.6 ± 1.4 (9)</td>
<td>NS</td>
</tr>
<tr>
<td>b6</td>
<td>Contra</td>
<td>300 400 4</td>
<td>−5.6 ± 3.2 (13)</td>
<td>−7.8 ± 0.5 (8)</td>
<td>*</td>
</tr>
<tr>
<td>b7</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−12.2 ± 5.6 (8)</td>
<td>−14.2 ± 3.6 (66)</td>
<td>NS</td>
</tr>
<tr>
<td>b8</td>
<td>Contra</td>
<td>100 400 2</td>
<td>−3.7 ± 1.1 (11)</td>
<td>−3.8 ± 0.3 (19)</td>
<td>NS</td>
</tr>
<tr>
<td>b8</td>
<td>Contra</td>
<td>100 400 2</td>
<td>−7.0 ± 1.9 (6)</td>
<td>−7.8 ± 0.5 (310)</td>
<td>*</td>
</tr>
<tr>
<td>b10</td>
<td>Contra</td>
<td>300 400 2</td>
<td>−16.8 ± 4.5 (6)</td>
<td>−17.1 ± 1.1 (16)</td>
<td>NS</td>
</tr>
<tr>
<td>b11</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−25.7 ± 5.6 (6)</td>
<td>−25.4 ± 3.4 (300)</td>
<td>NS</td>
</tr>
<tr>
<td>b12</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−4.7 ± 1.5 (11)</td>
<td>−4.8 ± 1.5 (11)</td>
<td>NS</td>
</tr>
<tr>
<td>b13</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−5.4 ± 1.5 (14)</td>
<td>−5.6 ± 1.0 (4)</td>
<td>NS</td>
</tr>
<tr>
<td>b17</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−8.5 ± 1.6 (9)</td>
<td>−8.6 ± 0.6 (20)</td>
<td>NS</td>
</tr>
<tr>
<td>e3</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−4.7 ± 0.9 (11)</td>
<td>−4.2 ± 0.3 (14)</td>
<td>NS</td>
</tr>
<tr>
<td>e4</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−6.9 ± 4.1 (10)</td>
<td>−8.4 ± 1.0 (54)</td>
<td>NS</td>
</tr>
<tr>
<td>e6</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−6.7 ± 3.0 (10)</td>
<td>−7.5 ± 1.6 (24)</td>
<td>NS</td>
</tr>
<tr>
<td>e8</td>
<td>Contra</td>
<td>200 400 2</td>
<td>−9.1 ± 2.6 (11)</td>
<td>−8.5 ± 0.9 (98)</td>
<td>NS</td>
</tr>
<tr>
<td>b14</td>
<td>Contra</td>
<td>200 600 2</td>
<td>−8.9 ± 1.3 (11)</td>
<td>−8.9 ± 0.6 (23)</td>
<td>NS</td>
</tr>
<tr>
<td>b16</td>
<td>Contra</td>
<td>200 600 2</td>
<td>−6.5 ± 1.6 (11)</td>
<td>−7.9 ± 0.1 (5)</td>
<td>*</td>
</tr>
<tr>
<td>b9</td>
<td>Ipsi</td>
<td>200 400 2</td>
<td>−9.2 ± 5.6 (13)</td>
<td>−8.2 ± 1.0 (149)</td>
<td>NS</td>
</tr>
<tr>
<td>e2</td>
<td>Ipsi</td>
<td>200 400 2</td>
<td>10.7 ± 2.7 (12)</td>
<td>9.0 ± 0.7 (17)</td>
<td>NS</td>
</tr>
<tr>
<td>b3</td>
<td>Ipsi</td>
<td>200 600 2</td>
<td>18.7 ± 10.5 (9)</td>
<td>18.6 ± 5.6 (115)</td>
<td>NS</td>
</tr>
<tr>
<td>e1</td>
<td>Ipsi</td>
<td>200 600 2</td>
<td>5.5 ± 1.7 (18)</td>
<td>6.8 ± 0.3 (5)</td>
<td>NS</td>
</tr>
<tr>
<td>e7</td>
<td>Ipsi</td>
<td>200 600 2</td>
<td>5.7 ± 2.2 (7)</td>
<td>6.6 ± 1.4 (43)</td>
<td>NS</td>
</tr>
</tbody>
</table>

Comparison between electrically evoked movements and visually triggered gaze shifts of matched amplitude initiated from similar eye and head positions. The mean ± SD values (number of trials under brackets) of horizontal amplitude (gaze and eye) and eye-head delay is documented for electrically evoked movements (stimulation) and visually triggered movements (visual). *P < 0.05 [Mann-Whitney U test (U-MW)]. Some cases are empty because we could not find visually guided movements with gaze amplitude and starting head position that matched with those of electrically evoked movements.
A significant correlation, indicating a dependency between eye and head horizontal peak velocities, was found in only 2 of 17 sites (sites b4 and e3).

Figure 5 shows the relationship between the horizontal peak velocity and amplitude for gaze shifts (eye + head; top), eye saccades (middle), and head movements (bottom) evoked electrically from all sites (●), using the same stimulation parameters (200 ms, 400 Hz, 2 T), and separately for each monkey (left: monkey B; right: monkey E). The relationship obtained with visually triggered gaze shifts (○, □, ◦) is also shown for comparison (see figure legend for details). For both electrically evoked and visually triggered movements, the horizontal peak velocity of contralateral gaze, eye, and head movements increased with horizontal amplitude.

**Ipsilateral movements**

Figure 6 shows the time course of typical ipsilateral gaze (A and C) and head (B and D) movements evoked by electrical microstimulation in the cFN. The illustrated sites (b9 in A and B and e2 in C and D) were located caudal (1.3 and 0.6 mm, respectively) and dorsal (−0.5 mm) to sites b7 and e8, both of which evoked contralateral movements. For each site, microstimulation also evoked staircase saccades with a mean latency of 59 and 62 ms (values for sites e2 and b9, respectively) after stimulation onset. Similar to contralateral movements, the amplitude of gaze shifts was variable. In the majority of stimulation trials, staircase saccades were evoked. The horizontal amplitude of gaze shifts (top) ranged from 3.3 to 23.1° for site b9 and from 7.2 to 15.1° for site e2. The vertical amplitude of gaze shifts (bottom) ranged from 3.2 to 17.8° for site b9 and from 0.3 to 5.7° for site e2. Ipsilateral movements of the head were sometimes observed but their amplitude was very small: the horizontal amplitude ranged from 0.1 to 5.5° for site b9 (B), and from 1.1 to 12.9° for site e2 (D), whereas the vertical amplitude ranged from −0.7 to 2.7° (site b9) and from −2.5 to 1.1° (e2). The latency of head movements ranged from 46 to 84 ms for site b9 and from 60 to 80 ms for site e2.

The average horizontal and vertical amplitude of ipsilateral gaze and head movements (stimulation parameters: frequencies = 400 and 600 Hz, duration = 200 ms, current = 2 T) are shown in Fig. 2 (positive values of horizontal amplitude, numerical values in Table 1). The average horizontal amplitude of gaze shifts ranged from 5.5° (e1) to 19.7° (b3), whereas their average vertical amplitude ranged from 0.5° (e7) to 5.0° (e2).
The latency of gaze and head movements ranged from 54 to 64 ms (gaze) and from 62 to 74 ms (head).

Similar to contralateral movements, ipsilateral gaze shifts were mostly composed of staircase saccadic eye movements. The relationship between the amplitude of ipsilateral gaze shifts and the amplitude of their ocular component is shown in Fig. 7 for the sites shown in Fig. 6 (sites b9 and e2) and for a site evoking large gaze shifts (e1). For both horizontal (left) and vertical (right) components, the slope of the relation between the eye amplitude and gaze amplitude was close to
unity (horizontal component: 0.92, 0.93, and 0.93, vertical component: 0.92, 0.99, and 1.06 for sites b9, e2, and e1, respectively) and the zero y intercept (horizontal component: −0.01, 0.25, and 0.17; vertical component: 0.33, 0.09, and −0.07) indicates that the gaze displacements were mostly performed by saccadic movements of the eyes. The summary of the regression parameters (slopes, y intercepts and $R^2$) for the other sites is shown in Table 2. For the horizontal component, the slope values ranged from 0.76 to 0.93, the y intercepts from −0.13 to 1.32 and the variance accounted for by the linear regression from 90 to 100%. For the vertical component, the slope values ranged from 0.86 to 1.06, the y intercepts from −0.07 to 0.42 and the variance accounted for by the linear regression from 72 to 96%. When the horizontal amplitude of gaze shifts was compared with that of the associated saccadic eye movements (Wilcoxon test), small but statistically significant differences were found for all sites (average difference $\pm$ SD = 0.24 ± 1.5°). Concerning the vertical amplitude comparison, a statistically significant difference was found in two sites (e1 and e7).

Like electrically evoked contralateral movements, the horizontal amplitude of ipsilateral movements was compared with...
that of visually-triggered gaze shifts (see Table 3). The amplitudes and the starting positions of gaze and head were matched for both types of movements, and a statistically significant difference in eye amplitude (Mann-Whitney U test) was observed in only one site (e1), whereas the average eye-head delay was significantly different in two sites (e2 and e7).

Increasing the frequency of stimulation did not increase the probability of observing head movements. In three sites tested with identical stimulation current (site b9, e1, and e2), increasing stimulation frequency from 400 to 600 Hz did not significantly alter the occurrence of head movements ($\chi^2$ test, $P > 0.05$). The horizontal head amplitude was increased in only one site (e1, average difference = 0.8°), whereas the vertical head amplitude remained unchanged. A statistically significant decrease in the latency of head movements was observed in two sites (average differences = −12 and −30 ms for sites b9 and e1, respectively).

Figure 8 illustrates the velocity profiles of horizontal and vertical components of electrically evoked ipsilateral eye saccades and head movements evoked at three sites (b9, e2, and e1; stimulation parameters: 200 ms, 400 Hz, and 2 T for sites b9 and e2 and 200 ms, 600 Hz, and 2 T for site e1). Eye saccades and head movements were moving with the same horizontal and vertical directions in sites b9 and e2. For site e1 ($n = 18$ trials), both the eye (4.9 ± 1.6°) and the head (1.2 ± 0.4°) were moving toward the left, but the direction of vertical components was slightly different: the eye moved upward (3.3 ± 1.1°) while the head barely moved vertically (−0.2 ± 0.2°). Similar to contralateral movements (see Fig. 4), the peak velocities were variable during ipsilateral gaze shifts. The horizontal peak eye velocities of the first gaze displacement ranged from 151 to 380°/s (site b9), from 264 to 558°/s (e2) and from 85 to 415°/s (e1), whereas the vertical peak velocities ranged from 150 to 334°/s, from 50 to 220°/s, and from 54 to 239°/s for sites b9, e2, and e1, respectively. Concerning head movements, the horizontal peak velocity of the first detected movement ranged from 5 to 64°/s (b9, 100% of trials), from 21 to 76°/s (e2, 100% of trials), and from 12 to 37°/s (e1, 83% of trials), whereas the vertical peak velocity ranged from 3 to 26°/s (b9), from 4 to 21°/s (e2), and from 4 to 14°/s (e1). A correlation was found between horizontal peak velocity and amplitude of the gaze shifts ($R = 0.84$, 0.96, and 0.91 for b9, e2, and e1, respectively). Significant correlations were also found between
gaze duration and gaze amplitude ($R = 0.92, 0.86$, and $0.56$ for $b9$, $e2$, and $e1$, respectively).

The relationship between horizontal peak velocity and amplitude of ipsilateral gaze shifts is shown in Fig. 5 (left: monkey B; right: monkey E, right part of each graph), for electrically evoked movements ($\bullet$: 200 ms, 400 Hz, 2 T) and for visually triggered gaze shifts ($\circ$, $\square$, $\diamond$). Similar to visually guided gaze shifts, horizontal peak gaze velocity of electrically evoked movements increased with horizontal gaze amplitude. In addition, electrically evoked movements showed that the peak velocity tended to be lower than the peak velocity of visually guided movements.

No significant changes in the amplitude or latency of electrically evoked gaze shifts were observed when the monkeys’ head was released. The horizontal and vertical gaze amplitudes were not significantly different between gaze shifts under head-restrained and -unrestrained conditions (Wilcoxon test, average differences $= 1.7 \pm 8.1$ and $0.0 \pm 3.1^\circ$ for horizontal and vertical component, respectively). Neither did the gaze latency significantly change between head-restrained and -unrestrained conditions (average difference $= 7 \pm 9$ ms).

Finally, the dependency between the evoked eye and head movements was also tested for each site by analyzing the correlation between their horizontal peak velocities. A significant correlation, indicating a dependency between evoked eye and head peak velocities, was found in two sites (sites $b9$ and $e1$).

**DISCUSSION**

Based on the observations made in the head-unrestrained monkey after cFN inactivation (see **INTRODUCTION**), it has been proposed that the cFN output influences the neural network involved in moving the eyes in the orbit, i.e., a neural stage which is functionally situated after that gaze-related (or target-related) signals split into separate premotor commands for moving the eyes and the head (Quinet and Goffart 2005, 2007a). The purpose of this study was to further test this hypothesis by examining whether electrical microstimulation of the cFN could evoke movements of the head and, perhaps, unravel some head-related function that inactivation experiments did not show. Even though stimulation trains were relatively long ($200–300$ ms), we found that evoked gaze shifts were small in amplitude and were primarily composed of saccadic eye movements. Head movements were observed in some sites, but they were small in amplitude ($mean = 2.4^\circ$). Neither the amplitude nor the occurrence of head movements was changed by increasing stimulation frequency or current. Interestingly, in some cases, the directions of gaze and head movements were different, and on occasion, completely opposite to each other. We discuss our results in relation to past studies and speculate on the potential roles of the caudal fastigial nuclei in the generation of orienting gaze shifts toward a visual target.

**Comparison with past studies in the head-restrained monkey**

Our findings indicate that high-frequency electrical microstimulation of the fastigial oculomotor region (FOR) evoked saccadic eye movements that were either ipsi- or contralateral to the stimulated side. Similar observations were made in past studies in the head-restrained monkey (Goffart et al. 1998; Murakami et al. 1991; Noda et al. 1988; see also Cogbell et al. 1977; Ron and Robinson 1973). In addition, we found that the electrically evoked saccades were very small in amplitude. This observation is compatible with the results reported by Noda et al. (1988). Indeed, as Noda and colleagues noted (see their Fig. 6, C and D), the amplitude of electrically evoked saccades ranged from 3 to 13° for ipsilateral movements (in comparison with the $5–16^\circ$ range in our study) and from 2 to 10° for contralateral movements ($3–26^\circ$ here).

Our study provides additional information regarding the variability in the amplitude of saccades evoked electrically from FOR stimulation. Such information was not available in past reports. Indeed, we have shown that the amplitude of saccades was more variable (see our Figs. 1, 2, and 6) than those suggested by Noda et al. (1988); see their Fig. 5). Two reasons can explain these apparently different results. First, the apparent lower variability in Noda’s study could be due to differences in the duration of stimulation trains. In their study, the duration of stimulation trains (20 ms) was 5–15 times shorter than the durations tested here, leaving the possibility that their saccades were truncated. Second, we found that the variability in amplitude was larger for the sites that evoked larger movements (gaze and head). This observation could not be deduced from Noda’s report. It is worth reminding that we could not find any evidence that the variability of saccade amplitude was due to the variability in starting eye position. The finding that saccades did not have constant amplitudes despite constant stimulation parameters could be due to a modulatory, as opposed to triggering, function of FOR in saccade generation. It could also be due to the fact that our microstimulation was applied unilaterally, whereas FOR activity is bilateral during natural visually guided saccades (Fuchs et al. 1993; Kleine et al. 2003; Ohtsuka and Noda 1991).

In agreement with the results of Noda and colleagues, we also found that ipsilateral saccades were evoked from the sites located more dorsal and caudal than the sites where contralateral saccades were elicited. Based on the recording of saccade-related units alone, we could not predict whether our stimulation (using a 600 Hz stimulation train) would evoke an ipsi- or a contralateral saccade. Noda et al. (1988) showed that ipsilateral saccades were elicited from electrically stimulating the dorsocaudal portion, whereas contralateral saccades were evoked from stimulating the ventromedial region. Because local injection of bicuculline in the fastigial nucleus suppressed the elicitation of ipsilateral saccades, they proposed that ipsilateral saccades were produced by stimulating the afferent axons of Purkinje cells in the oculomotor vermis (Fujikado and Noda 1987), whereas contralateral saccades resulted from activating the efferent axons of cFN neurons that projected toward the saccade generator in the contralateral ponto-medullary reticular formation (see also Sato and Noda 1992). The latter conclusion is compatible with the projections of FOR neurons toward the contralateral ponto-medullary reticular formation (PMRF) (Carpenter and Batton 1982; Noda et al. 1990). Projections toward the rostral interstitial nucleus of the medial longitudinal fascicularis (riMLF) have also been documented, but they are relatively minor in comparison with those toward the PMRF (Sato and Noda 1991). Moreover, the saccadic aspect of electrically evoked movements suggests that microstimulation activated the reticular saccade-related regions.
orthodromically rather than retrogradely. Indeed their retrograde activation would have led to eye movements with constant velocity (Cohen and Komatsuzaki 1972; Gandhi et al. 2008) and not to saccades with bell-shaped velocity profiles (see Figs. 4 and 8) and with relatively high peak velocities (see Fig. 5).

One may argue that saccades evoked from FOR electrical stimulation occur from the recruitment of saccade-related neurons in the rostral superior colliculus (SC). The staircase nature of evoked saccades would be compatible with this possibility (Freedman et al. 1996; Paré et al. 1994; Roucoux et al. 1980). However, this view raises several problems. On the one hand, if fastigio-tectal projections are bilateral as reported by May et al. (1990), it becomes unclear how bilateral activation of the rostral SC would lead to saccades with amplitudes of ~10°. On the other hand, if fastigio-tectal projections are contralateral as reported by Noda et al. (1990), stimulating axons of FOR neurons should evoke ipsilateral (not contralateral) saccades because SC projections toward the PMRF are also crossed. The observation that FOR stimulation evokes contralateral saccades is not compatible with this second possibility. Finally, one set of observations argues against the idea that saccades evoked by FOR stimulation involve a trans-collicular route. These observations come from perturbation experiments that consisted of testing compensation for an unexpected change in eye position prior to a saccade toward a flashed target. Such compensation has been shown to happen when the change in eye position is induced by electrical microstimulation of SC (Sparks and Mays 1983). When the change in eye position is elicited by electrical microstimulation of FOR, the correction saccade does not compensate for the perturbation and misses the target by an error equal to the change in eye position (Noda et al. 1991). In other terms, FOR stimulation activates neural elements that do not include the SC but involve the pontine reticular formation (Sparks et al. 1987). The saccadic aspect of evoked saccades could result from the recruitment of a large population of burst neurons in the contralateral PMRF due to diffuse fastigio-reticular projections (Noda et al. 1990) while the staircase aspect of evoked saccades would result from the interplay between the stimulation-induced excitation of burst neurons and the inhibition exerted by omnipause neurons (Paul and Gnadt 2006). As for the role of fastigio-tectal projections, our current working hypothesis is that they are involved in orienting gaze toward foveal targets during fixation (Goffart et al. 2006; Guerrasio et al. 2008; Hafed et al. 2008, 2009).

The neural mechanisms generating ipsilateral saccades during microstimulation of the dorso-caudal fastigial nucleus still remain unexplained. Some neurons in the cFN project toward the ipsilateral vestibular nucleus via the juxtaarestiform body (Batton et al. 1977; Sugita and Noda 1991), but stimulation of this pathway does not evoke any saccade (Noda et al. 1992). This result is compatible with the observations made by Ohtsuka et al. (1992) in a patient suffering from a lesion localized in the right superior cerebellar peduncle and juxtaarestiform body, whose saccades were intact while rightward smooth pursuit eye movements were impaired. Thus vestibular projections from cFN seem to be involved in the generation of pursuit eye movements rather than saccades. The fastigio-tectal pathway could be involved in the elicitation of ipsilateral saccades during FOR stimulation (see preceding text). However, two sets of observations are not compatible with this possibility. The first set of observations comes from studies performed by Noda’s group: if ipsilateral saccades were evoked by recruiting a fastigio-tectal pathway, they should be insensitive to an injection of bicuculline (GABA_A antagonist) in the FOR. The results showed that local injection of bicuculline in the FOR suppressed the elicitation of ipsilateral saccades (Noda et al. 1988; Sato and Noda 1992), suggesting the stimulation recruited afferent axons from Purkinje cells rather than efferences from the FOR. The second set of observations comes from studies performed in our group. Indeed, when long (100–300 ms) and relatively low-frequency (100 Hz) stimulation trains were applied to the dorso-caudal portion of the fastigial nucleus, microstimulation did not evoke ipsilateral saccades as one would expect if saccade-related neurons in the contralateral deep superior colliculus were retrogradely activated (Stanford et al. 1996). Instead, contralateral saccades were evoked and their onset was timed to stimulation offset rather than to stimulation onset (example given in Fig. 2 of Goffart et al. 1998, 2003; unpublished results). Moreover, when this low-frequency train was applied while the monkey was generating saccades toward a visual target, saccade accuracy was impaired in a way that was similar to the deficits observed after local injection of muscimol (GABA_A agonist) in the cFN: the horizontal component was hypermetric for ipsilateral saccades, hypometric for contralateral saccades and an ipsipulsion affected vertical saccades (see Fig. 3 in Goffart et al. 2003) with a magnitude that increased with saccade amplitude/duration (unpublished observations). These muscimol-like effects of the microstimulation are compatible with the idea that the microstimulation activates the axons of Purkinje cells innervating the FOR and inhibits their target neurons (Noda et al. 1988). Considering that the activation of FOR neurons produces contralateral saccades, it is possible that ipsilateral saccades evoked from stimulating the oculomotor vermis or the dorsocaudal region of the fastigial nucleus result from activity in the opposite FOR which is unbalanced by activity in the stimulated FOR.

Fastigial nucleus and the modulation of eye and head movements

Our findings contrasts with the report of Magoun et al. (1935) that stated that stimulating the fastigial nucleus and the neighboring white matter elicited eye, head, and trunk movements in the head-unrestrained anesthetized monkey (see also page 146 in Dow and Moruzzi 1958). Gaze shifts evoked in our study were barely accompanied with any head movements. When they were, the amplitude of head movements was small (mean = 2.4°). In addition, increasing the frequency (from 400 to 600 Hz) or the intensity of stimulation (=120 μA) did not increase the occurrence or amplitude of head movements. The difference between Magoun’s study and ours is likely due to the volume of activated elements. Indeed, Magoun et al. (1935) used “a bipolar needle-like electrode, <1 mm in diameter, with the tips of the two wires separated by a distance of 1 mm”, whereas we used fine tungsten unipolar microelectrodes with very small tips (<5 μm). Moreover, the currents used in our study (see METHODS) were considerably lower than those used by Magoun and his colleagues (1.5 A). Finally, the sites that we stimulated were restricted to a very small region where saccade-related bursts of activity were recorded. Magoun’s
The failure to systematically evoke head movements may result from our experimental approach. Indeed in our study, the microstimulation was not delivered while the head was moving toward a target (see METHODS). If the FOR exerts a modulatory role over the generation of head movements, an influence on head movements may be realized only when the head is already moving (for example see Courjon et al. 2004 for a demonstration of the SC influence on reaching movements by stimulating during the on-going movement). Unfortunately, we did not test this possibility. Unit recording studies show that some neurons in the cFN modulate their activity during passive head movements. These neurons fire during earth-vertical axis passive rotations of the head. According to Büttner et al. (1991), most of them display a type II vestibular response (increase in firing rate when the head rotates toward the contralateral side). They are also modulated during suppression of the vestibuloocular reflex and during contralateral smooth pursuit eye movements, but they were not active during saccades or fixation. These observations and the report by Büttner et al. (1994) about patients, who presented saccade hypermetria but well-preserved smooth pursuit eye movements after bilateral lesions of the fastigial nuclei, suggest that the cerebellar control of saccadic and slow eye movements involves separate pathways. But another study by Fuchs et al. (1994) reported the existence of neurons in the cFN that had smooth pursuit sensitivity and also discharged a burst of spikes for saccades in one or more directions.

The rarity of observed head movements may suggest that the cerebellar region involved in the control of head movements is located elsewhere and that the zone explored in this study is essentially oculomotor. This possibility is consistent with several observations made after muscimol injection in the FOR: dysmetria of gaze shifts due to dysmetric saccades of the eyes in the orbit and changes in the relationship between amplitude and peak velocity of eye saccades and not for head movements (Quinet and Goffart 2005, 2007a). It is also consistent with anatomical observations in which neck motoneurons, in the upper cervical C2 segment, receive direct and indirect projections from neurons located in more rostral regions of the fastigial nucleus. These neurons are located rostrally relative to those projecting to the peri-abducens region (Robinson et al. 1994). The indirect projections involve the medial regions of the contralateral nucleus reticularis gigantocellularis (Batton et al. 1977; Robinson et al. 1994) the microstimulation of which elicits ipsilateral head movements (Cowie and Robinson 1994; Quessy and Freedman 2004).

Recording studies report that numerous neurons in the rostral fastigial nuclei (rFN) are sensitive to passive head rotation around the horizontal and vertical earth-fixed axes (Büttner et al. 1991; Gardner and Fuchs 1975; Shaikh et al. 2005; Siebold et al. 1997, 1999). To our knowledge, there is no published work describing the consequence of inactivating or stimulating the rFN on head movements in the primate. One study in the cat (Pélisson et al. 1998) reported asymmetric movements of the head after muscimol injection in the rFN (hypermetria for ipsilesional movements, hypometria for contralateral ones). Moreover, changes in the relationship between the amplitude and peak velocity of gaze shifts (gaze main sequence) were only observed during very large gaze shifts (see their Fig. 12C), suggesting that the main sequence relationship was impaired for head movements and not for the eye saccades. These observations and the anatomical data from Robinson et al. (1994) are compatible with an involvement of the rFN in the control of head movements. It is possible that head movements observed in our study resulted from a diffusion of the stimulating current toward neural elements located more rostrally in the fastigial nucleus.

Does the FOR stimulation evoke small-amplitude gaze shifts?

Our findings that FOR stimulation primarily elicited saccades with minor head movements might suggest that the FOR is involved in the control of small gaze shifts. It is known that small visual gaze shifts in the monkey are characterized by relatively small head contributions and long eye-head delays (Freedman and Sparks 1997; Phillips et al. 1995; Tomlinson and Bahra 1986). The inconsistent head movements that accompanied electrically elicited saccades (Figs. 1 and 4 and Table 1), the apparent similarity between electrically evoked and visually triggered movements (Fig. 5 and Table 3) and the projections toward the rostral SC (May et al. 1990; Noda et al. 1990) would be compatible with this view (but see first section of DISCUSSION for problems raised by this fastigio-tectal route). However, this idea raises several problems. First it assumes that microstimulation elicited an orienting response as opposed to an unnatural motor pattern. Corneil et al. (2002) and Chen (2006) provided EMG and kinematical evidence that stimulation of the dSC or of the FEF, respectively) evokes unnatural movements (see also Chen and Tehovnik 2007). Figure 4C (our study) shows examples where gaze and head moved in opposite directions during the stimulation train (see also Fig. 2B in Pélisson et al. 2003b). Significant differences in eye amplitude and in eye-head delay were also found between electrically evoked movements and visually triggered gaze shifts (matched in amplitude and starting positions of gaze and head). These results indicate that FOR stimulation can evoke movements that do not look like small, visually triggered gaze shifts. The second problem concerns the nature of gaze shifts that are supposed to be evoked and to which the electrically evoked movements should be compared. Gaze shifts toward auditory targets are endowed with smaller eye-head delays, larger head movements, and smaller concomitant ocular saccades than visually triggered movements (Goossens and van Opstal 1997). Thus movements evoked by FOR stimulation would more likely differ from small gaze shifts directed toward auditory targets. Moreover, it is not certain that the stimulation elicited an orienting response (like those directed toward external stimuli) as opposed to an oculomotor response which is triggered internally. Examples of internally triggered movements are spontaneous saccades or vestibularly driven quick phases generated in the dark. In summary, it would be premature to conclude that FOR stimulation activates a pathway leading to the generation of small gaze shifts.

In fact, three observations raise doubts about an involvement of the FOR in the control of only small gaze shifts. First, the dysmetria that affects gaze shifts after muscimol injection in the FOR is not restricted to small saccades but also affects medium- and large-sized (≥40°) eye-head gaze shifts initiated from the straight ahead position (Quinet and Goffart 2005,
injection in both FORs. But the bilateral hypometria (see also Quaia et al. 1999), one should expect to observe could progressively adapt their size (Scudder and McGee 2007). Although not explicitly stated, this view considers the input from the FOR and rely only on the collicular drive, leading to gaze hypometria. This scenario is rather attractive because it provides a neural mechanism by which saccades would progressively adapt their size (Scudder and McGee 2003) or even permit saccadic foveation of moving targets (Keller et al. 1996). According to this “dual-drive” hypothesis (see also Quaia et al. 1999), one should expect to observe hypometria of left- and rightward gaze shifts after muscimol injection in both FORs. But the bilateral hypermetria observed after bilateral FOR inactivation (Robinson et al. 1993; our unpublished observations) is hardly compatible with this view. Finally, according to Goffart et al. (2004), the hypometria of contralateral saccades (and gaze shifts) observed after unilateral FOR inactivation is due as much to the burst from saccade-related neurons in the opposite and unaffected FOR as to the suppression of activity in the injected FOR (see also discussion in Quinet and Goffart 2007a).

Conclusion

In agreement with anatomical (Robinson et al. 1994) and inactivation studies (Quinet and Goffart 2005, 2007a), the present study provides additional observations suggesting that the caudal fastigial nucleus is an oculomotor region that is not directly involved in the control of head movements. In the primate, the primary function of this region would be to modulate oculomotor commands generated in the brain stem for the proper foveation of visual targets. In cats, where the orienting response also relies on movements of the head, the caudal fastigial nucleus is involved in orienting the head (Goffart and Pélisson 1998; Goffart et al. 1998). Inactivation of the caudal portion of the medial cerebellar nucleus in animals having a relatively poor vision (e.g., rodents) should also be very informative for understanding the more general role of this region in the functional organization of orienting behaviors (see Bower 1997).

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