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RESEARCH ARTICLE

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Spatial characteristics of neurons in the central mesencephalic reticular formation (cMRF) of head-unrestrained monkeys

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Abstract Prior studies of the central portion of the mesencephalic reticular formation (cMRF) have shown that in head-restrained monkeys, neurons discharge prior to saccades. Here, we provide a systematic analysis of the patterns of activity in cMRF neurons during head unrestrained gaze shifts. Two types of cMRF neurons were found: presaccadic neurons began to discharge before the onset of gaze movements, while postsaccadic neurons began to discharge after gaze shift onset and typically after the end of the gaze shift. Presaccadic neuronal responses were well correlated with gaze movements, while the discharge of postsaccadic neurons was more closely associated with head movements. The activity of presaccadic neurons was organized into gaze movement fields, while the activity of postsaccadic neurons was better organized into movement fields associated with head displacement. We found that cMRF neurons displayed both open and closed movement field responses. Neurons with closed movement fields discharged before a specific set of gaze (presaccadic) or head (postsaccadic) movement amplitudes and directions and had a clear distal boundary. Neurons with open movement fields discharged for gaze or head movements of a specific direction and also for movement amplitudes up to the limit of measurement (70°). A subset of open movement field neurons displayed an increased discharge with increased gaze shift amplitudes, similar to pontine burst neurons, and were called monotonically increasing open movement field neurons. In contrast, neurons with non-monotonically open movement fields demonstrated activity for all gaze shift amplitudes, but their activity reached a plateau or declined gradually for gaze shifts beyond specific amplitudes. We suggest that presaccadic neurons with open movement fields participate in a descending pathway providing gaze signals to medium-lead burst neurons in the paramedian pontine reticular formation, while presaccadic closed movement field neurons may participate in feedback to the superior colliculus. The previously unrecognized group of postsaccadic cMRF neurons may provide signals of head position or velocity to the thalamus, cerebellum, or spinal cord.

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Introduction

The premise of this paper is that the mesencephalic reticular formation (MRF) participates in the control of gaze movements (the sum of eye-in-head and head-in-space movements). The central portion of the MRF (the cMRF) receives strong projections from the superior colliculus (SC), a midbrain region whose neurons discharge in association with shifts of gaze, not individual movements of the head or eyes (Freedman and Sparks 1997a). In turn, the cMRF provides descending fibers that target the paramedian zone of the pontine reticular formation (PPRF) and the nucleus reticularis gigantocellularis (NRG), regions of the pons and medulla that participate in the generation of eye and head movements, respectively (Edwards 1975; Langer and Kaneko 1984; Buttner-Ennever 1988; Cowie et al. 1994). In addition, the cMRF has descending projections to the upper cervical spinal cord (Castiglioni et al. 1978). Due to the evidence of gaze-related neurons in the SC, one

objective of this study was to determine if tecto-recipient neurons of the cMRF were better correlated with either gaze or head movement. A second motivation was to determine if cMRF neurons participate in the generation of the dynamics of head or gaze movement. This latter goal is addressed in the accompanying paper (Pathmanathan et al. 2005).

Neurons in the intermediate and deep layers of the SC are activated before a specific set of gaze movement amplitudes and directions and project to the cMRF (Moschovakis et al. 1988a; Chen and May 2000). Movement fields of the SC are topographically arranged such that neurons towards its rostral portion discharge before small gaze shifts while cells in the caudal portion of the SC discharge before large gaze shifts (Wurtz and Goldberg 1972; Sparks et al. 1976; Munoz and Guitton 1985). Electrical microstimulation of the SC elicits a gaze shift of particular amplitude and direction to the opposite side, which is dependent upon location of stimulation (Robinson 1972; Stryker and Schiller 1975; Cowie and Robinson 1994; Stanford et al. 1996). Therefore, SC neurons carry a *spatial representation* of the contralateral field of movement (e.g., Sparks et al. 1976; Munoz and Wurtz 1995; Sparks and Gandhi 2003).

These physiologic characteristics of the SC are quite distinct from neurons located downstream in the PPRF, the immediate premotor staging area for the generation of the horizontal component of rapid eye movements (Luschei and Fuchs 1972; Robinson 1973; Keller 1974; Henn and Cohen 1976; Van Gisbergen et al. 1981; Hepp and Henn 1983; Cullen and Guitton 1997). A similar area of burst neurons is located in the rostral interstitial nucleus of the MLF (riMLF) for the generation of the vertical component of saccades (Buttner-Ennever and Buttner 1978; King and Fuchs 1979; Henn et al. 1991). The discharge of cells in either the riMLF or the PPRF persists for the duration of the saccade and the peak frequency of their firing is related to the peak velocity of the upcoming saccade (Keller 1974; Van Gisbergen et al. 1981; Cullen and Guitton 1997). Prolonged electrical stimulation of these regions produces saccades whose amplitude is dependent upon the duration of stimulation, while saccade velocity is dependent upon the rate of stimulation up to approximately 500 pulses per second after which the velocity saturates (Cohen and Komatsuzaki 1972; Keller 1974). Such characteristics constitute a *temporal representation* of the upcoming saccade. Thus, the discharge of spatially coded neurons in the SC must be rapidly transformed into the temporal sequence of discharges required to drive the muscles (a spatial to temporal transform).

The PPRF and the riMLF both receive a portion of the descending output of the SC. To immediately (i.e., within one synapse) convert signals coded spatially in the SC into the temporal pattern of firing found in the PPRF and riMLF, either of the two conditions must be met: (1) the discharge of downstream-projecting SC neurons must increase monotonically as saccade amplitude increases, in other words their movement fields must be open or (2) the density of SC neurons projecting to (or the number of boutons contacting) a particular PPRF or riMLF neuron must increase in a precise topographic manner. In either condition, the duration of the SC discharge would need to approximate the duration of the gaze shift. Some studies have suggested that the duration of the SC discharge can approximate saccade or gaze duration (Berthoz et al. 1986; Waitzman et al. 1991; Keller and Edelman 1994; Munoz and Wurtz 1995; Guitton et al. 2003). However, use of the transynaptic label, rabies virus, injected into the lateral rectus muscle of monkeys (Grantyn et al. 2002) has shown that the direct anatomical connections between the SC and PPRF may not be sufficient to mediate the spatial to temporal transformation. While the density of cells labeled in the intermediate and deep layers of the SC increased with caudal location, this anatomic gradient could not completely specify the spatial to temporal transformation. The authors suggested that an increase in synaptic density (see Moschovakis et al. 1998) or a change in the efficacy of each bouton could account for the lower than expected number of projections.

Other lines of evidence also argue against the hypothesis that the spatial to temporal transformation between the SC and PPRF is accomplished solely by direct anatomic connections. First, physiologic experiments have suggested that primate SC neurons provide powerful excitatory activity to *long-lead* burst neurons and not the medium-lead burst neurons in the PPRF (Raybourn and Keller 1977; Keller et al. 2000). Second, anatomic data generated using transynaptic labeling show that SC neurons are at least three, not two, synapses removed from the abducens motoneurons (Grantyn et al. 2002). Taken together, these findings suggest that spatially encoded information in the SC is transformed by parallel groups of long-lead burst neurons that have large, open movement fields into the temporal drive exhibited by the premotor medium-lead burst neurons. We hypothesize that one pathway utilizes pontine long-lead burst neurons and a second pathway makes use of long-lead burst neurons with open movement fields in the MRF.

The MRF receives the bulk of the collicular outflow in the midbrain (Edwards and de Olmos 1976; Harting et al. 1980; Grantyn and Grantyn 1982; Cohen and Buttner-Ennever 1984; Moschovakis and Karabelas 1985; Moschovakis et al. 1988b; Chen and May 2000) and has direct projections to the PPRF, omnipause neurons (OPNs) of the raphe interpositus, and NRG (Langer and Kaneko 1984; Buttner-Ennever 1988; Cowie et al. 1994). Several lines of evidence suggest that the MRF, located lateral to the oculomotor nucleus and bounded rostrally by the fields of Forel and caudally by the brachium conjunctivum, could participate in processing collicular outflow. The cMRF, the portion of the MRF caudal to the posterior commissure, has been implicated in the control of horizontal eye movements (Cohen et al. 1986; Waitzman et al. 1996, 2000). Neurons in the cMRF discharge before contraversive sac-

cades, with a given neuron preferring a particular subset of saccade amplitudes and directions. Thus, cMRF neurons have movement fields. Moreover, retrograde rabies labeling has shown that neurons within the cMRF are two synapses away from the abducens motoneurons and thus are *closer* to the PPRF than the SC neurons (Grantyn et al. 2002). Previous work has shown that cMRF neurons carry neural signals that are closely related to the dynamics (velocity and position) of saccades (Waitzman et al. 1996). However, that study was limited to monkeys whose heads were stationary. Thus, previous measurement of cMRF movement fields has been restricted to approximately $\pm 30°$ of primary position.

The primary objective of the current paper was to expand the understanding of the spatial properties of cMRF neurons using monkeys whose heads were unrestrained. A completely unexpected finding was evidence of group of cMRF neurons whose discharge occurred *after* the end of the saccade (postsaccadic) and whose spatial properties were most closely associated with head and not gaze movement. This finding provided an opportunity to contrast the spatial properties of pre- and postsaccadic cMRF neurons to determine if they were, in fact, two distinct populations. A preliminary account of these results has been presented previously in abstract form (Pathmanathan et al. 2002).

Methods

Surgical procedures

All experiments were approved by the Animal Care and Use Committee of the University of Connecticut Health Center and complied with the principles enunciated in the "Guide for the Care and Use of Laboratory Animals" (NIH publication No. 86-23, revised 2001). Under isoflurane anesthesia, a 3-turn stainless steel eye coil (Cooner Wire AS-632) was implanted in the coronal plane beneath the conjunctiva of one eye of four male rhesus monkeys (*Macaca mulatta*, animals H, P, R, and Y; Judge et al. 1980). Recording chambers (Crist Instruments) were stereotaxically positioned over the right (monkeys P and Y), left (monkey H), and both (monkey R) cMRFs. Eye coil wires and a head fixation device were secured to the skull using dental acrylic and vitalium screws. Postsurgical pain was controlled with either buprenorphine (1 mg/kg) or ketorolac (30 mg every 6–8 h).

Isolation of the cMRF

The depth and the rostral–caudal extent of the oculomotor nuclei were identified first via electrical microstimulation and the characteristic discharge of oculomotor neurons. The cMRF was then localized by moving 2–4 mm lateral to the oculomotor nuclei. At the conclusion of experiments, monkeys were killed under deep pentobarbital anesthesia followed by cardiac perfusion. All recording sites were reconstructed by reference to the physiologic location of the oculomotor nuclei and small pressure injections of fluorescent microbeads (Luma Flor; Waitzman et al. 1996).

Training and experimental paradigm

Monkeys were trained to direct their gaze at 1° diameter target spots rear-projected onto a tangent screen 87 cm away and subtending 70°×40° of visual angle in an otherwise darkened room. To restrict body and shoulder movements, but allow head movement, monkeys wore a vest (Lomir Biomedical) clipped at the back and shoulders to a standard primate chair (Crist Instruments). All neurons reported here were recorded with the head unrestrained. For monkeys P and Y, a neck plate limited the downward head movements to no greater than 20° from the straight-ahead position, but horizontal and upward head movements were unrestricted. The monkeys were not trained to independently control head or eye position, and the variation in initial eye in head position was not great enough to dissociate relationships to eye versus gaze movements. Thus, we refer to "gaze movement" or "gaze shift" when the head is unrestrained (i.e., combined head and eye movements) and "eye movement" or "saccade" when referencing work when the head was restrained.

Target position was under computer control and could be shifted to any location on the screen using an *X*–*Y* galvanometer (GSI Lumonics). Initially, the animal fixated a target for 500–1,000 ms. If gaze position was stable during this interval, then the fixation target was extinguished and a new target was presented elsewhere on the screen. Monkeys were required to perform gaze shifts using either one of the two paradigms. In the first paradigm we determined the direction preference of a cMRF neuron. Targets appeared at the center of the screen and then shifted 5°–30° away in 5° increments of amplitude to one of the eight centrifugal directions. If the cell isolation was maintained, monkeys performed the second paradigm that generated larger amplitude gaze shifts from an initial target to a second peripheral target located up to 70° away in 10° increments, which required shifting gaze across the midline. Successful trials were rewarded with juice delivered through a tube that moved with the head. Unrewarded spontaneous movements were performed in complete darkness and were recorded between these trained behaviors.

Data collection

All experiments were controlled and monitored by computer running REX 4.1, which specified mirror galvanometer and fixation spot positions, administered the reward, recorded gaze and head movements, and collected unit activity. Gaze and head positions were

recorded using the magnetic search coil technique (Riverbend Electronics; Robinson 1963) and sampled at either 500 Hz (monkeys P, H, and R) or 250 Hz (monkeys P and Y). Head position was recorded with a coil fixed to the reward apparatus on the head. The linearity of the field coils was established using an artificial eye that was rotated to a known amount within different portions of the field. Torsional signals were not recorded. To limit non-linearity, only movements made within ±40° of straight-ahead gaze are included. However, translational (i.e., side to side and front to back) movements of the head could not be recorded. We defined a linear region of recording in the center of the field coil by shifting a test coil by up to ±4 cm in the nasal-occipital and intra-aural axes and found no degradation of the rotational (horizontal or vertical) signals. This distance far exceeded any translational signal the animal could generate. After collecting the data for monkey R, a head channel recording error was discovered. This error, a horizontal position dependent vertical offset, was produced by improper calibration of the vertical phase adjustment. No similar error was found in the gaze channel or in any of the other monkeys. We corrected this problem by experimentally recreating the error with a test coil. The corrected data was verified by ensuring that eye and gaze directions were identical. Eye position was calculated offline as the difference between gaze and head positions.

During all experiments, fine tip (< 10 μ), resin-coated tungsten electrodes (1–5 MΩ, Frederick Haer Corporation) were positioned by a hand-screw microdrive (Bela Microdrive) and lowered into the brain through cannulae positioned within the recording cylinder using a grid with 1 mm spacing (Crist Instruments). The microelectrode signal was amplified (10,000×) and filtered (Butterworth filter, 80 dB/decade, Corner Frequency (F_c = 3,000 Hz) to remove the high-frequency coil signals. Spike events were detected using a threshold and time–amplitude window discriminator (BAK Instruments) at 1 ms resolution. Unit activity was collected only if the waveform was stable and readily distinguishable from background. Data collection for a particular neuron was concluded if either the unit waveform changed or the animal stopped participating. Using these criteria and recording with the head unrestrained imposed a severe penalty because sufficient data for analysis could be obtained from less than 1/3 of the isolated neurons.

Data analysis

Saccadic movements were detected using an automated program based on movement velocity. Velocity and acceleration were calculated offline by differentiation of the gaze, head, and eye position signals (Euler differentiation, followed by low-pass, zero-phase lag FIR filtering with a 15 element window, F_c = 150 Hz). Periods where eye and gaze velocities exceeded 20°/s, or head velocity exceeded 15°/s, and the amplitude was greater than 1° were defined as movements. Results were visually inspected to ensure accuracy. The data presented include visually guided gaze shifts and, when noted, spontaneous gaze shifts recorded in complete darkness. All errors are reported as standard deviations (±1 SD).

To generate movement fields we counted the number of spikes (NOS), which occurred in a variable interval that began 30 ms before gaze (or head) onset to gaze (or head) end, minus the spontaneous background firing rate times the duration of the movement. We calculated the background firing rate as the 500 ms of spontaneous activity just before and after the current trial while the monkey sat in total darkness (excluding regions of activity within ±50 ms of a spontaneous gaze movement, but not excluding periods when the head was moving and the gaze was stable). The adjusted spike counts were then plotted as a function of the *change* in horizontal and vertical gaze amplitudes, as if the gaze movement had originated from the origin (i.e., retinotopic coordinates). An analysis using a fixed counting interval of 50 ms was also used and provided similar results (not shown). The spontaneous discharge rate of the neuron was subtracted for two reasons: (1) it corrected for the longer duration associated with larger amplitude movements and (2) some cMRF neurons have very high background discharge rates that would have systematically biased the spike count of longer intervals associated with larger amplitude saccades (Waitzman et al. 1996).

Once the spike counts were calculated, we smoothed the movement field data using a 5°×5° averaging window (“a pixel”) stepped by 2°. This generated a grid of average spike intensity versus x–y movement amplitude. A pixel of particular color reflecting the average intensity of response was displayed only if there was a minimum of three movements within the averaging window. We classified each movement field as either “closed”, “monotonically open”, or “non-monotonically open” based on a slice across the best-fit movement field (i.e., gaze for presaccadic and head for postsaccadic neurons) that included primary position (i.e., straight ahead gaze) and the optimal discharge of the neuron (See Results Figs. 5, 6, 8) (Munoz and Wurtz 1995). Cross sections which had a defined peak, with activity that returned to baseline as movement amplitude increased, were defined as “closed”. Cross sections that had increased activity for increased movement amplitude to a peak followed by either a gradual reduction of activity (which did not return to baseline) or a plateau were defined as “non-monotonically open”. Finally cross sections that demonstrated activity that increased monotonically with saccade amplitude were defined as “monotonically open”.

Results

We recorded 67 neurons in four rhesus monkeys during head-unrestrained gaze shifts to visual targets. Of these,

27 neurons discharged before gaze shifts (“presaccadic neurons”), 2 neurons paused during gaze shifts, 22 neurons began to discharge *after* gaze shift onset (“postsaccadic neurons”), and 16 neurons discharged during the experimental paradigm but were not associated with vision or gaze shifts. Figure 1 shows sample trials from a pre- and postsaccadic neuron. Presaccadic neurons began to discharge before the onset of gaze shifts and their peak discharge occurred before peak gaze velocity (Fig. 1a). In contrast, postsaccadic neurons began to discharge *after* gaze onset and their peak discharge occurred after peak gaze velocity (but while the head continued to move, Fig. 1b). The 49 gaze-related neurons could be separated into pre- and postsaccadic categories based on the latency between peak discharge and peak gaze velocity (Fig. 1c). For presaccadic neurons, the peak discharge occurred 18.5 ± 2.9 ms before peak gaze velocity (Fig. 1c and Table 1). The latency from the peak discharge of presaccadic neurons to the peak *head* velocity was 53.5 ± 21.2 ms (excluding trials during which presaccadic neurons discharged but there was no head movement). In contrast, for postsaccadic neurons the peak discharge occurred 116.6 ± 65.5 ms *after* the peak gaze velocity (Fig. 1c) and an average of 11.6 ± 23.8 ms after peak *head* velocity (Table 1). Note that the histogram of latencies from peak discharge to peak gaze velocity was far more variable for postsaccadic than for presaccadic neurons (Fig. 1c). One neuron had its peak discharge an average of 3 ms *before* peak gaze velocity. However, it was classified as postsaccadic because the onset of its discharge began after gaze shift onset and the bulk of its discharge occurred after the end of the gaze movement. The latencies of individual pre- and postsaccadic neurons are listed in Supplementary Electronic Tables 1 and 2, respectively.

Pre- and postsaccadic neurons could not be distinguished on the basis of their anatomic locations within the cMRF (Fig. 2). Reconstruction of recording locations of pre- and postsaccadic neurons demonstrated that both types of neuron could be encountered on the same electrode penetration (which occurred in two tracks) and were distributed throughout the rostral–caudal extent of the cMRF. However, postsaccadic neurons were more likely to be encountered in the rostral and medial portions of the cMRF.

Discharge characteristics of cMRF neurons

The differences between the discharge patterns of pre- and postsaccadic neurons were clearly evident when their activity was aligned in raster form. Presaccadic neurons (Fig. 3, left column) were characterized by a burst that began before the onset of the gaze shift (Fig. 3a, trials aligned on gaze onset), whereas postsaccadic neurons (Fig. 3, right column) began to discharge *after* the start of gaze shifts (Fig 3b, trials aligned on gaze onset). To determine if cMRF neurons were associated with other aspects of the gaze shift, the same rasters were re-aligned on the start of the head movement (Figs. 3c, d). The onset of the discharges of postsaccadic cMRF neurons were much better aligned on

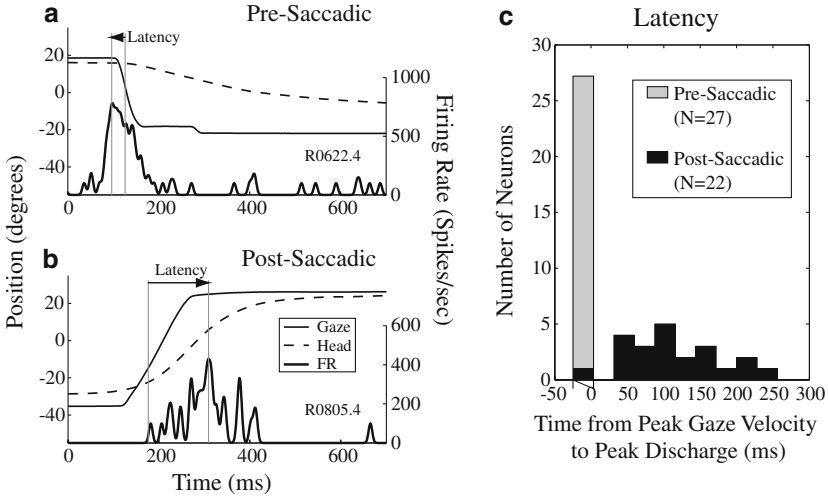

Fig. 1 Comparison of pre- and postsaccadic cMRF neurons on the basis of latency to peak gaze velocity. **a** All presaccadic neurons began to discharge before gaze shifts, and their peak discharge occurred on average 18.5 ms before peak gaze velocity. Traces are gaze position (*solid line*), head position (*dashed line*), and spike density (*bold solid line*) of a single trial. The first vertical line is peak discharge and the second vertical line is peak gaze velocity. **b** Postsaccadic neurons discharged after the onset of gaze shifts and their peak discharge typically occurred after the peak gaze velocity (but while the head continued to move). Conventions are the same as **a**, but the first vertical line is peak gaze velocity and the second vertical line is peak discharge. **c** Histogram of the latencies from peak discharge to peak gaze velocity for all cMRF neurons studied. Note that the peak discharge of presaccadic neurons (*gray bar*) always preceded peak gaze velocity, while the peak discharge of postsaccadic neurons (*black bars*) followed the peak gaze velocity (with one exception). The latency to peak gaze velocity of postsaccadic neurons was more variable than the latency of presaccadic neurons

Table 1 Spatial characteristics of cMRF neurons

	Latency target onset to movement onset (ms)	Latency peak discharge to peak gaze velocity (ms)	Latency peak discharge to peak head velocity (ms)	Correlation: NOS to amplitude	Slope: NOS to movement amplitude (spikes per degree)
Presaccadic cells				Gaze	Gaze
C($N=10$)	161.0 ± 38.3	18.4 ± 2.4	36.9 ± 12.9	0.29 ± 0.26	0.19 ± 0.11
NMO ($N=10$)	152.5 ± 20.1	17.9 ± 3.0	57.7 ± 22.8	0.51 ± 0.14	0.28 ± 0.24
MO ($N=7$)	159.0 ± 16.9	19.7 ± 3.6	66.2 ± 15.6	0.73 ± 0.20	0.32 ± 0.30
All presaccadic	157.3 ± 27.0	18.5 ± 2.9	53.5 ± 21.2	0.48 ± 0.27	0.26 ± 0.22
Postsaccadic cells				Head	Head
C ($N=6$)	187.2 ± 73.6	−129.1 ± 60.3	−12.2 ± 29.1	0.33 ± 0.19	0.83 ± 0.68
O ($N=16$)	138.1 ± 19.4	−122.0 ± 68.6	−11.4 ± 22.6	0.60 ± 0.18	0.51 ± 0.33
All postsaccadic	151.5 ± 41.4	−116.6 ± 65.5	−11.6 ± 23.8	0.53 ± 0.22	0.60 ± 0.46

head onset than gaze onset (compare Fig. 3d, b). We found no association between the discharge and subsequent corrective gaze shifts for any postsaccadic neuron (Figs. 3e, f; same trials as in Figs. 3c, d excluding trials indicated by asterisks, which did not contain corrective gaze shifts). The discharge of presaccadic neurons declined sharply by gaze end (Fig. 4a, same trials as Fig. 3a, aligned on gaze end). On the other hand, postsaccadic neurons not only began to discharge after gaze onset, but also often continued to discharge after the gaze had stabilized and the head continued to move (Fig. 4b, same trials as Fig. 3b). These findings suggested that presaccadic neurons were best associated with gaze movement, while postsaccadic neurons were not.

Spatial characteristics of cMRF neurons

Previous recordings had suggested that a subset of cMRF neurons related to eye movement had movement fields that blanketed most of the contralateral field of movement up to the 30° limit of measurement (Waitzman et al. 1996). Because the current experiments could generate gaze shifts of up to 70° horizontal and 40° vertical amplitudes, we tested the hypothesis that the movement fields of cMRF neurons were larger than previously documented (see limitations in Methods). Gaze shifts greater than 30° were initiated contralateral to the direction of movement and crossed the midline.

Evidence of two distinct groups of cMRF neurons, pre- and postsaccadic, necessitated the use of two different counting intervals to construct movement fields for each cell (Figs. 5, 6). The gaze movement associated counting period included all the spikes in the interval which began 30 ms before gaze onset to the end of the gaze shift (Fig. 5a, shaded region), as has been used previously (Waitzman et al. 1996). The head movement associated counting period included all the spikes in the interval that began 30 ms before head movement onset and concluded with the end of the head movement (Fig. 5b, shaded region). Note that the entire "gaze-associated interval" was typically included within the "head-associated interval" because both intervals began at similar times but the head interval was often much longer. Thus, activity associated with gaze movements would be present in *both* the gaze and head-associated intervals, whereas activity occurring during the head movement (but after the end of the gaze movement) would be evident *only* in the head-associated interval. All gaze and head movements that met velocity criteria (see Methods) were included in the generation of the movement field. Movements that were associated with no activity are shown in blue, while the highest associated activity is represented by red. The white areas represent vectors for which no movement data was obtained (the animal did not make a gaze or head movement to that region during the recording session).

Two presaccadic neurons are displayed in Fig. 5. As can be seen from the movement fields, activity of presaccadic neurons was clearly evident in the gaze-associated interval (Figs. 5c, e), and was still apparent when analyzed using the head-associated counting interval (Figs. 5d, f). Note that the animals typically did not make vertical head movements during vertical gaze displacements less than 30°. Vertical gaze shifts less than 30° were typically made with eye movements alone (Freedman and Sparks 1997b). Because of this, the head movement fields were often compressed in the vertical direction relative to the gaze movement fields (compare Figs. 5c, d). If no head movement occurred for a gaze shift, then no data is displayed in the head movement field.

The activity of presaccadic neurons occurred before and during horizontal gaze shifts to the contralateral side. One cell had a closed movement field (R0622.4, Fig. 5c), in that it discharged for only a subset of movement amplitudes and demonstrated little activity beyond a specific amplitude. Note that the head movement field also shows a peak of activity, which corresponds to the gaze movement field data. The second presaccadic cMRF neuron in Fig. 5 had a monotonically increasing (see below) open movement field (Fig. 5e). The head movement field showed an increased activation with larger amplitude of head movement (Fig. 5f). The spike counts displayed for the head

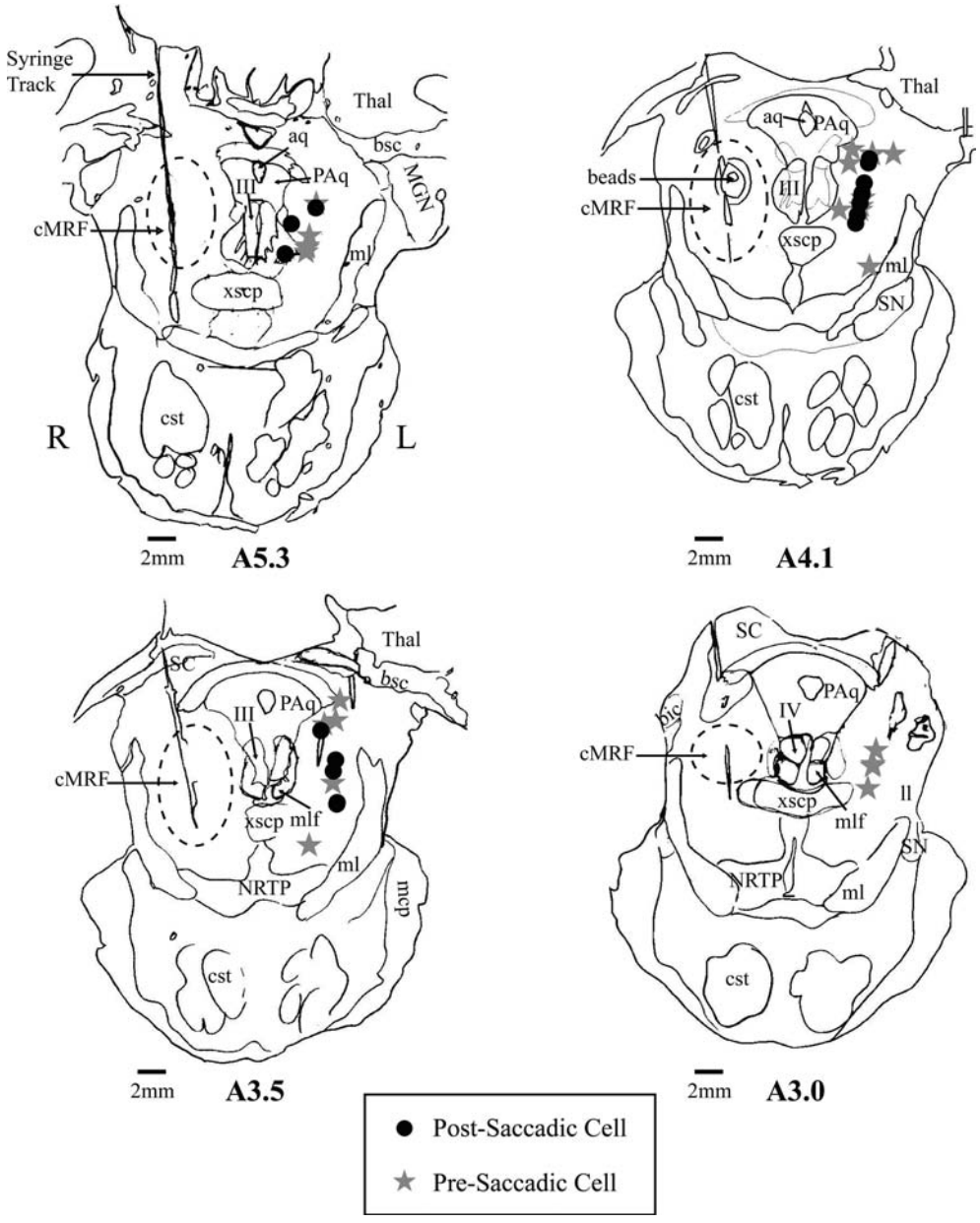

Fig. 2 Anatomic recording sites of all the cMRF cells from all four monkeys are shown on representative sections from one monkey. The location of all presaccadic (*stars*) and postsaccadic (*filled circles*) cMRF neurons from four monkeys are shown on one of the four representative coronal sections through the midbrain of monkey R (3.0–5.3 mm anterior to the inter-aural line). Locations were reconstructed based on depth and distance of recording relative to the oculomotor nuclei, stimulation results, and fluorescent bead injection sites. The cMRF (*dashed ellipse*) is defined as the portion of the reticular formation lateral to the oculomotor nucleus (*III*), medial to the lateral lemniscus, ventral to the SC, and dorsal to the brachium conjunctivum. Syringe track and location of one fluorescent bead injection is shown on the *right side* of monkey R. Note that this track and injection were made after the completion of neuron recordings from this monkey. All cells from other monkeys are shown on the *left side* of the brain stem for ease of presentation. *Right* (*R*) and *left* (*L*) are indicated on slice A5.3 (*upper left*). Abbreviations: *III* oculomotor nucleus, *IV* trochlear nucleus, *aq* aqueduct of Sylvius, *bsc* Brachium of the superior colliculus, *bic* brachium of the inferior colliculus, *cst* corticospinal tracts, *ll* lateral lemniscus, *ml* medial lemniscus, *MGN* medial geniculate nucleus, *mlf* median longitudinal fasciculus, *NRTP* nucleus reticularis tegmenti pontis, *PAq* periaqueductal gray, *SC* superior colliculus *SN* substantia nigra, *xscp* crossing of the superior cerebellar peduncle (brachium conjunctivum)

movement fields could be higher than the gaze movement fields due to longer counting intervals associated with head movements.

In contrast to the association of presaccadic neurons with gaze, the overwhelming majority of postsaccadic neurons (16/22) had large movement fields whose spike counts increased with increasing head, not gaze amplitude. Figure 6 displays gaze and head movement fields for two postsaccadic neurons. Little activity occurred during the counting interval associated with the gaze

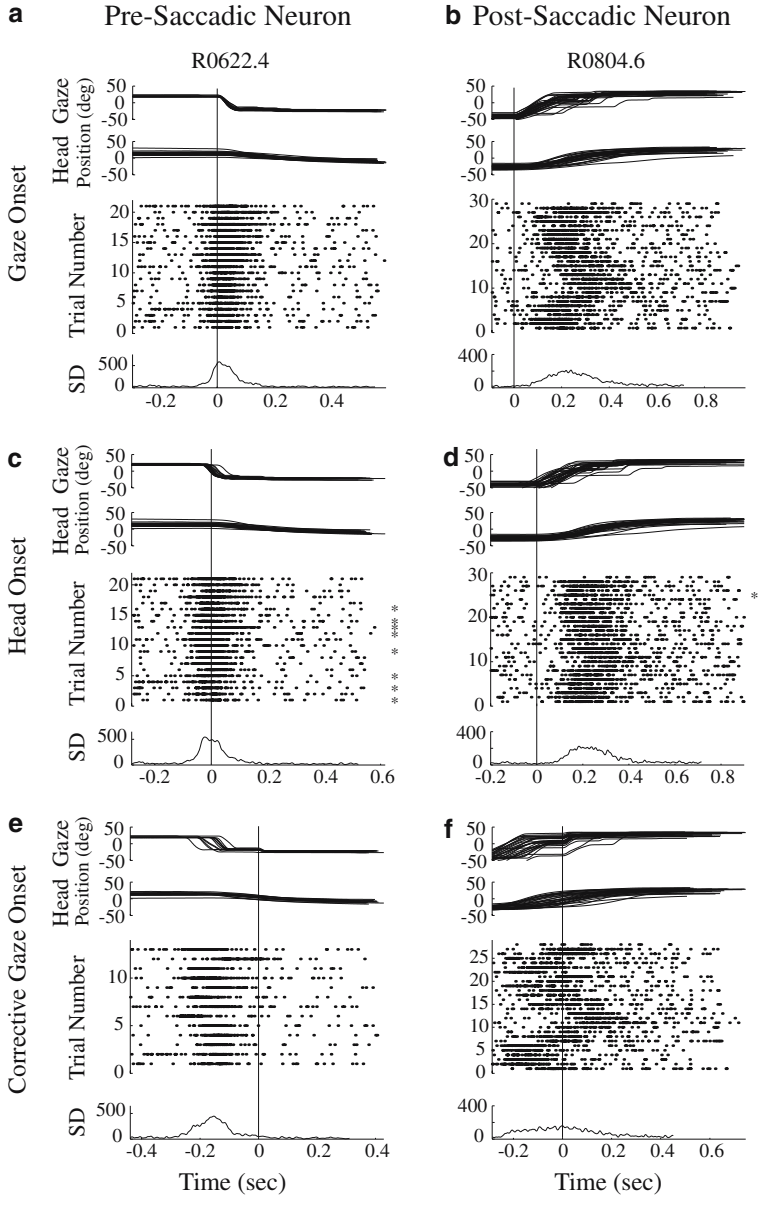

Fig. 3 Comparison of the two types of neurons recorded in the cMRF. The discharge of pre- (*left column*) and postsaccadic (*right column*) cMRF neurons were aligned on different parameters of the gaze shift. For each condition horizontal gaze position, horizontal head position, spike raster, and an average spike density (SD) are shown. In the rasters, each *line* represents a different trial, and each *dot* indicates an action potential. **a** and **b** are aligned on the onset of gaze. Notice that the presaccadic neuron begins to discharge before the onset of gaze **a** and the postsaccadic neuron begins to discharge after the onset of gaze movement **b**. **c** and **d** are aligned on head onset. Notice that the postsaccadic neuron begins to discharge after the head begins to move, but is much better aligned with the head than with the gaze movement onset (compare **b** to **d**). **e** and **f** are aligned on the corrective gaze shift. The same trials shown in **c** and **d** are re-aligned on the beginning of the *next* gaze shift (i.e., typically representing a corrective gaze movement). The *asterisks* to the right of each line of the rasters in **c** and **d** indicate trials that had no corrective movements

movement fields. As a result, the gaze movement fields appear nearly empty (regions colored blue in Figs. 6a, c). Because most of the activity of these postsaccadic neurons occurred following the gaze shift, the head-associated movement fields contained more robust responses (Figs. 6b, d). One cell had its best response for upward head movements of 15° or greater (Fig. 6b). The other cell had its best response for large horizontal head movements greater than 40° to the *ipsilateral* side (Fig. 6d), although it also discharged at a lower rate during large contralateral (leftward) head movements. It should be noted that the head movement fields were not as thoroughly explored as the gaze movement fields for two reasons: (1) our paradigm did not explicitly control the contribution of head movement to the overall gaze shift and (2) cells could not be held for the duration of time necessary to gather data on head movements in all directions and amplitudes.

For each neuron, the optimal point in either the gaze (presaccadic neurons) or head (postsaccadic neurons) movement field was calculated. However, we were unable to explore beyond the distal edges of the tangent screen (i.e., 70° horizontally and 40° vertically). Thus, these optimal points represent the optimum discharge of the *explored* fields and might be different had an even more expansive investigation been possible. Based on the optimal points of the tested field, pre- and postsaccadic neurons had several differences. Presaccadic neurons were typically horizontally tuned to the contralateral side, with optimal amplitudes ranging from 2° to 60° (Fig. 7, stars). Only 2 presaccadic neurons had optimal vectors that were directed more than ±45° from the horizontal and 2 of 27 presaccadic neurons produced their strongest discharge for ipsilateral gaze shifts. Cells with high spontaneous rates of firing were inhibited for ipsilateral movements. In contrast, postsaccadic cMRF

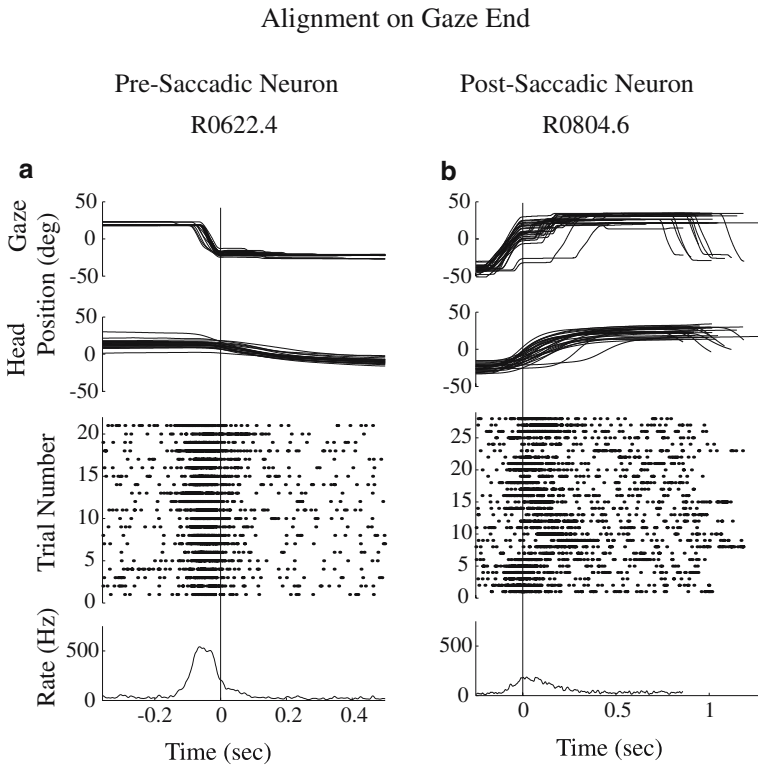

Fig. 4 Comparison of the two types of neurons recorded in the cMRF aligned on the end of the gaze shift. The discharges of the pre- **a** and postsaccadic **b** cMRF neurons shown in Fig. 3 were aligned on the end of the gaze shift. The traces for each cell are from *top* to *bottom*: horizontal gaze position, horizontal head position, spike raster and an average spike density of the displayed trials. Notice that the discharge of the presaccadic neuron is nearly over by gaze end **a**, while the discharge of the postsaccadic neuron was often just beginning with the end of the gaze shift **b**

neurons preferred large-amplitude head movements that varied in direction from purely horizontal to vertical (Fig. 7, filled circles). Six postsaccadic neurons had their highest discharge for ipsilateral head movements, 11 for contralateral head movements, and 5 for vertical head movements.

To compare the differences in the movement fields across the entire population of cMRF neurons, we constructed cross-sections (Fig. 8) by taking a slice across the activity in the movement field that included the central fixation point (i.e., primary position) and the optimal response. Spline fits to the cross-section data demonstrated three types of movement field response in presaccadic neurons: closed, monotonically open, and non-monotonically open (see Methods, and shown in Figs. 8a–c, f). Neurons that had "closed" movement fields (Figs. 5c, 8a) were essentially identical to the cMRF neurons described previously in head-restrained animals (Waitzman et al. 1996). The discharge of these neurons was greatest for specific amplitude and direction gaze shifts. These movement fields had both proximal and distal boundaries (Fig. 8a). In contrast, presaccadic neurons with open movement fields had no specific distal boundary (Figs. 5e, 8b, c). Open movement field neurons were of two types. One group had an increase in their discharge up to an optimal amplitude, but further increases in gaze amplitude resulted in reduced spike counts (i.e., "non-monotonically open" movement fields, Fig. 8c). Such movement fields are similar to those reported for open movement field build-up neurons in the SC (Munoz and Wurtz 1995). The spike counts of the remaining open movement field presaccadic cMRF neurons increased for gaze shift amplitudes up to the limit of measurement (Fig. 8b). Similar monotonically increasing movement fields have been reported in the long and medium-lead burst neurons of the PPRF (Henn and Cohen 1976; Scudder et al. 1988; Cullen and Guitton 1997; Sparks and Gandhi 2003). Presaccadic cMRF neurons were almost evenly distributed across these three categories (Fig. 8f).

Unlike presaccadic neurons, postsaccadic neurons demonstrated the strongest relationships between spike number and *head* movement amplitude. Most postsaccadic neurons (16/22) had open movement fields that demonstrated a linear relationship between spike number and head movement amplitude in the neuron's optimal direction (Fig. 8e). None of the postsaccadic neurons displayed non-monotonically open movement fields, but six postsaccadic neurons had closed movement fields (Fig. 8d). Another striking difference of postsaccadic neurons was that 8/22 responded during head movements in *both* the ipsilateral and contralateral directions (e.g., see Figs. 6d, 8e), albeit the response to the optimal direction occurred earlier (Supplementary Electronic Table 2).

A question raised by the cross-section analysis was the strength of the relationship between spike number and the amplitude of the ensuing gaze shift or head movement. When the relationship between gaze shift amplitude and spike number was tested (i.e., linear least squares), presaccadic neurons with monotonically open movement fields were more strongly correlated with gaze shift amplitude (mean correlation = 0.73 ± 0.20) than closed movement field neurons (mean correlation =

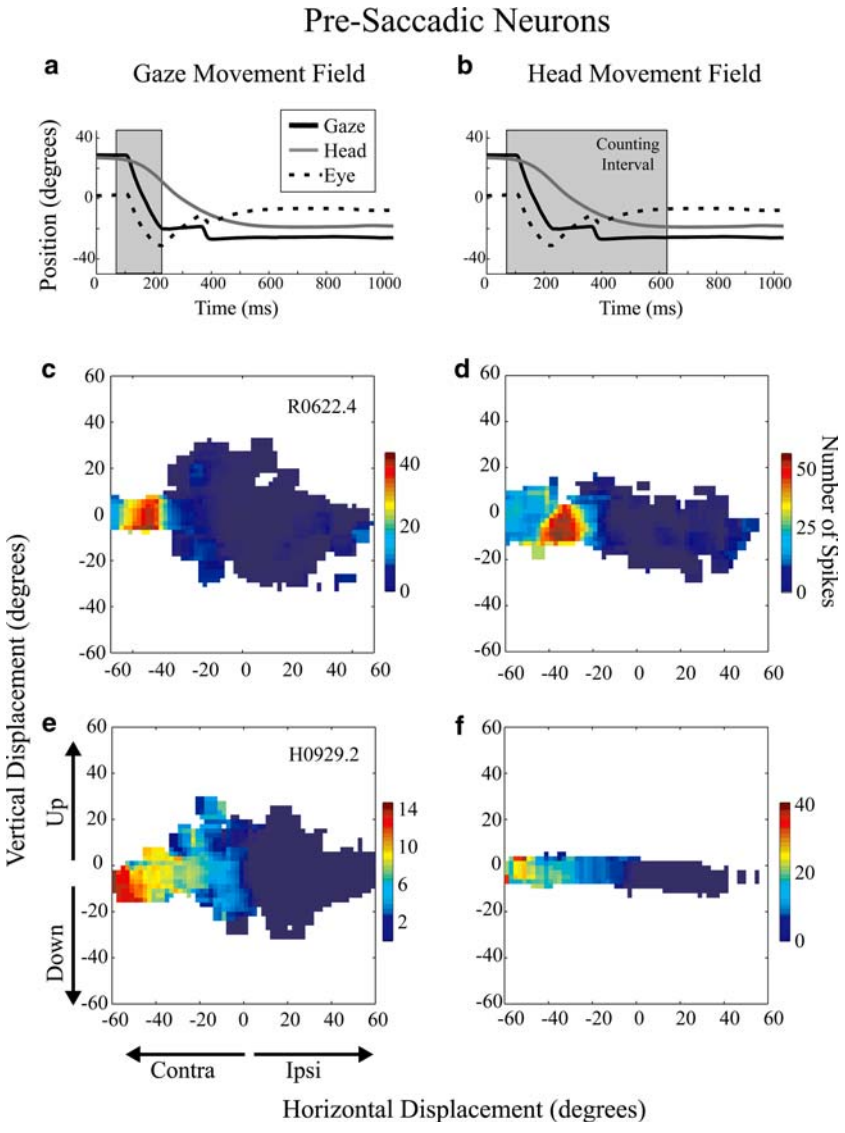

Fig. 5 Movement fields and analysis intervals for two presaccadic cMRF neurons. **a** The "gaze-associated" counting interval (*shaded region*) began 30 ms before gaze onset and ended with gaze offset. **b** The "head-associated" counting interval (*shaded region*) began 30 ms before head movement onset and ended with head end. The counts in each interval were corrected by the spontaneous background discharge measured in total darkness. Movement fields for each of the two presaccadic cMRF neurons are shown twice, once based on gaze displacement (*left column*, **c** and **e**) and once based on head displacement (*right column*, **d** and **f**). Higher activity is represented by red, while minimal activity is shown as *dark blue*. **c** and **d** The movement field of unit R0622.4 (*second row*) reached its peak discharge 40° to the contralateral side and declined rapidly thereafter. Thus, the movement field for this neuron was closed. Note that a similar arrangement of the activity found in the gaze-associated movement field was mirrored in the head movement field. **e** and **f** Contrast this response to a monotonically open movement field presaccadic neuron (H0929.2, *third row*) whose discharge increased with increased displacement to the contralateral side. Again the movement field was similar when displayed as a function of head displacement.

0.29 ± 0.26) (see Table 1). Furthermore, the slope of the best fit line was higher for monotonically open than closed movement field neurons, suggesting that the discharge of monotonically open movement field neurons encoded gaze shift amplitude with greater sensitivity (average slope = 0.32 ± 0.30 versus 0.19 ± 0.11 spikes per degree). Non-monotonically open movement field neurons had intermediate correlations (mean $r = 0.51 \pm 0.14$; slope of best-fit line = 0.28 ± 0.24 spikes per degree). Presaccadic neurons did not demonstrate relationships to head movement amplitude. The correlation coefficients and slopes of best-fit lines for individual presaccadic neurons are reported in Supplementary Electronic Table 1.

For "bidirectional" neurons, the slope of the linear relationship between spike number and head movement amplitude was higher for the optimal than the opposite direction (0.60 ± 0.46 versus 0.16 ± 0.25 spikes per degree) (see Table 1 and Supplementary Electronic Table 2). We found that postsaccadic neurons with monotonically increasing open movement fields had stronger correlations (i.e., linear least squares) between

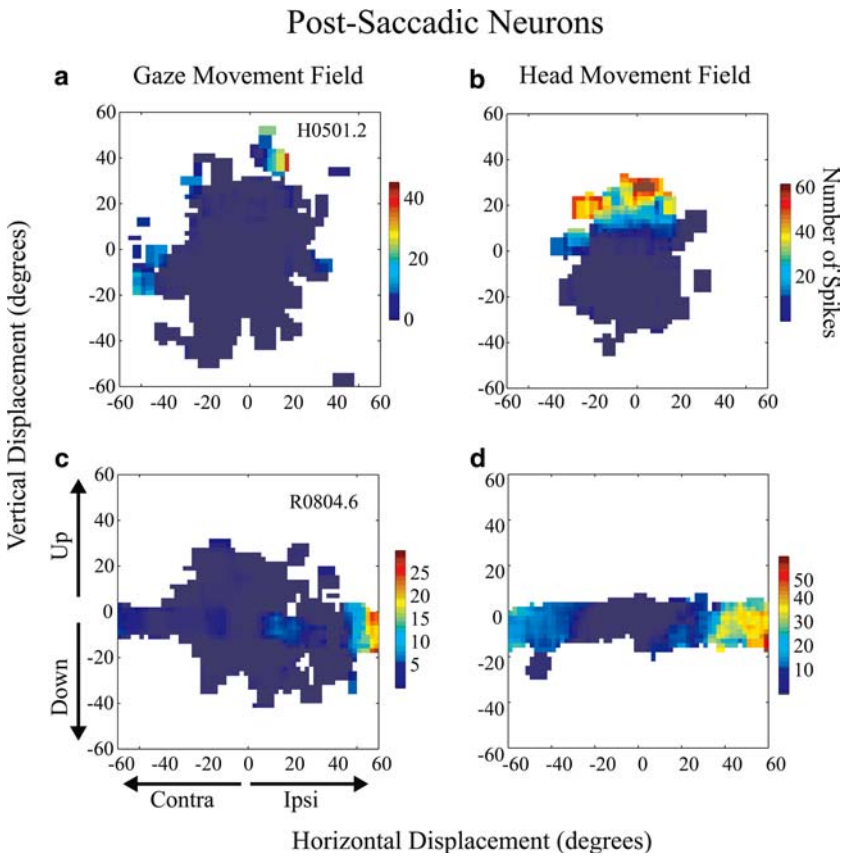

Fig. 6 Movement fields for two postsaccadic cMRF neurons. Movement fields of cMRF neurons were determined by counting the number of spikes in a "gaze" (**a** and **c**) and "head" (**b** and **d**) associated movement field (conventions as in Fig. 5). **a** and **b**: Unit H0501.2 (*first row*) had its highest discharge for vertical (primarily upward) head movements. Note the better organization of the activity when head **b** rather than the gaze **a** associated interval and displacement were utilized to construct the movement field. **c** and **d**: Unit R0804.6 (*second row*) was bidirectional and had its highest discharge for ipsilateral (rightward) head movements. It had weaker discharges for contralateral (leftward) movements. In all four panels, *red* is associated with higher and *dark blue* with lower number of spikes in the counting interval

head movement amplitude in the optimal direction and spike number (mean correlation = 0.60 ± 0.18; slope of best-fit line = 0.51 ± 0.33 spikes per degree) than closed movement field neurons (mean correlation = 0.33 ± 0.19; slope of best-fit line = 0.83 ± 0.68 spikes per degree). The correlations and slopes of the best-fit lines for individual postsaccadic neurons are listed in Supplementary Electronic Table 2.

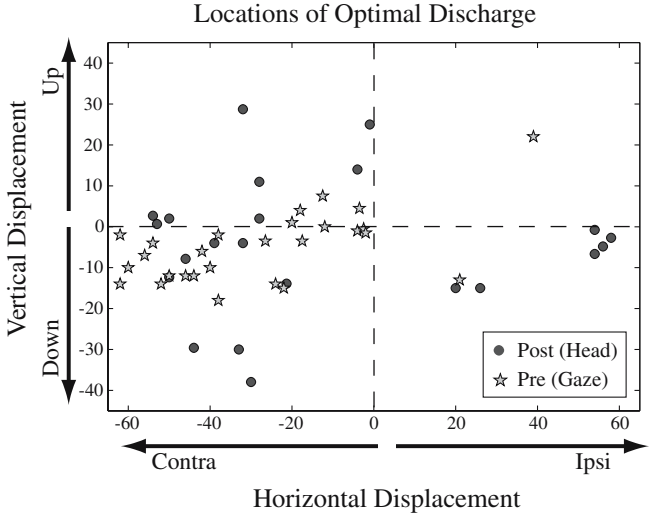

Fig. 7 Amplitude and direction of the optimal response for all 49 cMRF neurons. Each *symbol* represents the tip of a vector that originated from the origin (crossing of two dashed lines). The vectors indicate the amplitude and direction of the optimal response for each presaccadic (*grey stars*) and postsaccadic (*grey circles*) cMRF neuron reported here. Eight neurons responded best before ipsilateral movements, while the remaining neurons responded before movements to the contralateral side.

Discussion

Recording cMRF neurons in monkeys performing large reorienting gaze shifts has generated a number of novel findings. First, this technique demonstrated that the gaze displacement associated with the optimal discharge of cMRF neurons tended to be much larger than previously appreciated during head-restrained recordings (Waitzman et al. 1996). A second and unexpected result was the discovery of a group of postsaccadic cMRF neurons whose discharge began after the onset of the gaze shift and whose activity persisted following the end of the gaze shift. A third finding was that open movement field presaccadic cMRF neurons were of either of two types. Cells with non-monotonically increasing open movement fields resembled open movement field build-up and some burst neurons found in the SC (Munoz and Wurtz 1995). cMRF neurons with monotonically increasing open movement fields most closely resembled direction long-lead burst neurons previously described in the PPRF (Hepp and Henn 1983; Scudder et al. 1988; Cullen and Guitton 1997; Sparks et al. 2002). Overall,

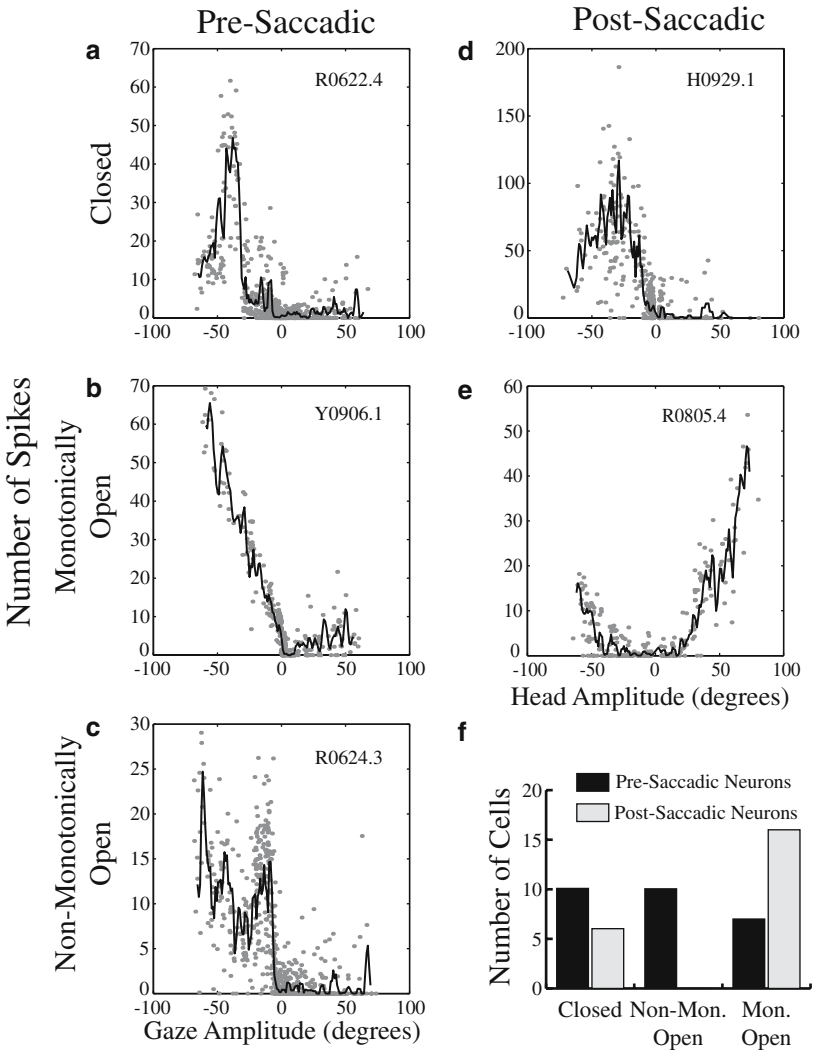

Fig. 8 Cross-sections across the movement fields of pre- and postsaccadic cMRF neurons. Cross-sections display spike counts associated with the movements along the vector connecting primary position (straight-ahead gaze) and the optimal location of the movement field (along the vector shown in Fig. 7). Negative amplitudes indicate contralateral gaze shifts and positive amplitudes indicate ipsilateral gaze shifts. To generate the cross-sections for presaccadic neurons (*left column*) we used the gaze-associated movement field, while the head-associated movement fields were used to generate the cross-sections for postsaccadic neurons (*right column*). *Dark lines* indicate spline fits of the data. The analysis was repeated for each neuron using peak discharge rate in the analysis interval rather than the total number of spikes and no change was observed in the results (not shown). **a** A presaccadic cMRF neuron whose activity increased, peaked, and then declined sharply was classified as having a closed movement field. **b** Cross sections that rose without a clear outer boundary were classified as "monotonically open". **c** Cross-sections demonstrating persistent activity for gaze shift amplitudes up to the limit of measurement but with a plateau or peak of activity for specific amplitude which then declined and did not reach baseline were classified as "non-monotonically open". **d** Postsaccadic cMRF neuron with a closed *head* movement field. **e** Activity of a different postsaccadic cMRF neuron that increased monotonically with increased head movement amplitude in both directions. **f** Histogram showing the numbers of presaccadic (*black bars*) and postsaccadic (*gray bars*) neurons displaying each of these types of movement field property. If the monotonically increasing and the non-monotonically increasing categories were combined, the majority of pre- and postsaccadic cMRF neurons had open movement fields. Abbreviations: *Non-Mon Open* Non-Monotonically Open, *Mon Open* Monotonically Open

alignment of the neural activity on movement onset suggested that the discharge of presaccadic neurons was more closely associated with gaze movements, while the discharge of postsaccadic neurons was more closely associated with head movements. Reconstruction of electrode tracks through the cMRF confirmed that pre and postsaccadic cMRF neurons are distributed throughout the extent of this structure and *not* in specific subregions.

There are several caveats associated with the current experiments which require consideration. Since our monkeys were not trained to independently change initial eye or head positions for gaze shifts of the same amplitude (Tu and Keating 2000; Gandhi and Sparks 2001), we were unable to cleanly dissociate eye and gaze signals. Similarly, the majority of the head movements were generated from within $\pm 10°$ of the nose pointing toward the fixation target. As a result, we could not

isolate a relationship between initial head or eye position and the discharge of cMRF neurons. In addition, all gaze and head signals were recorded using a two-dimensional coil system and thus the effects of torsion could not be characterized. Accordingly, we leave to future studies the tasks of distinguishing cMRF signals that are exclusively gaze from those that are related to eye movement, exploring the effects of initial eye and head positions, and investigating the relationship between torsion and cMRF discharge.

Characteristics of presaccadic cMRF neurons

Previous data in head-*restrained* monkeys have shown that cMRF neurons discharge in advance of saccades (Cohen et al. 1986; Waitzman et al. 1996; Handel and Glimcher 1997). We have now confirmed with the head unrestrained that the current set of presaccadic neurons share many of the physiologic properties of the previously reported set of head-restrained neurons (Waitzman et al. 1996). Both the previous and current sets of presaccadic neurons had similar latencies and both were closely associated with the rapid portion of gaze (head unrestrained) or eye (head restrained) movements. Furthermore, these two groups of neurons discharged predominantly for contralateral movements, albeit two neurons in the current set of data preferred ipsilateral gaze shifts. The new finding, which became evident as a result of utilizing large gaze shifts, was that the movement fields for 17/27 of the presaccadic neurons were open and that these neurons discharged for gaze shifts up to 70°. Although these neurons might have had distal boundaries beyond our measurement ability, they certainly have larger movement fields than previously appreciated. The spike counts associated with nearly half of the open movement field cMRF neurons were monotonically related to the amplitude of the overall gaze shift, a finding that has not been previously reported (Waitzman et al. 1996; Handel and Glimcher 1997). Such movement field properties are characteristic of the long and medium-lead PPRF burst neurons (Hepp and Henn 1983; Scudder et al. 1988). We suggest that cMRF presaccadic neurons with monotonically open movement fields have the proper activity to function in parallel with the tecto-pontine projections to the long-lead burst neurons of the PPRF (Raybourn and Keller 1977; Keller et al. 2000). Such a tecto-reticulo-pontine pathway could assist in developing the spatial to temporal transformation (Moschovakis et al. 1998; Grantyn et al. 2002) (see also Discussion of accompanying paper).

While the mechanisms for constructing PPRF long-lead burst neurons with "monotonically open" movement fields from the output of the SC have been hypothesized, the physiologic and anatomic details of the SC/cMRF interactions require some clarification. We suggest either of the two possibilities for presaccadic neurons. First, each presaccadic cMRF neuron could receive input from a series of neurons along an SC rostral to caudal meridian of constant direction (Fig. 9a). This would correspond to the direction preference of the cMRF neuron. To date, while the intermediate and deep layers of the SC project strongly to cMRF, evidence for stripe-like projections from the SC to the cMRF is lacking (Cohen and Buttner-Ennever 1984; Chen and May 2000). Another problem with this idea is that for a horizontal component of particular amplitude, the presaccadic discharge of open movement field cMRF neurons would be similar regardless of the vertical component of movement. As a result, the band of SC neurons contributing to the presaccadic cMRF movement field would have to be much wider than the gray region illustrated, approaching the checked area (Fig. 9a). A second possibility is that presaccadic cMRF neurons with open movement fields receive a higher density of boutons and/or projections from caudal SC neurons than from the rostral SC neurons (Fig. 9b, gradient). This would be similar to the connections documented by Moschovakis et al. (1998) and Grantyn et al. (2002) for the SC to PPRF projection. This idea would account for the evidence of larger movement fields and the discharge characteristics of presaccadic cMRF neurons, but again the distribution of SC neurons contributing to the activity of each cMRF neuron would have to be quite large. Either anatomic arrangement would suggest that the latency and physiologic activity of the subgroup of SC neurons and the presaccadic cMRF neurons to which they project are similar. Previous data, as well as that shown here, confirm that the presaccadic cMRF latency is comparable or only slightly shorter than that reported for SC neurons (e.g., 2 ms difference between the peak discharge and saccade onset for groups of SC and cMRF neurons recorded from the same animal; Waitzman et al. 1996). These findings were confirmed for the current study which demonstrated an average of 18.5 ms between peak discharge and peak gaze velocity for presaccadic neurons (Table 1). Most likely some combination of topographic projections to the cMRF from a strip of the SC or a gradient of activity from the SC would best account for the open movement field properties of the majority of presaccadic cMRF neurons.

Characteristics of postsaccadic cMRF neurons

Previous studies of the cMRF with the head restrained did not demonstrate the presence of neurons that discharge after the end of the gaze shift. There were four unique features of the postsaccadic cMRF neurons reported here. First, these neurons began to discharge after gaze onset, with the bulk of their discharge occurring following the end of the gaze shift (peak discharge occurring 116.6 ms after peak gaze velocity, on average). Second, these neurons had movement fields that were best defined using head, not gaze movements. Third, many had open movement fields with a nearly

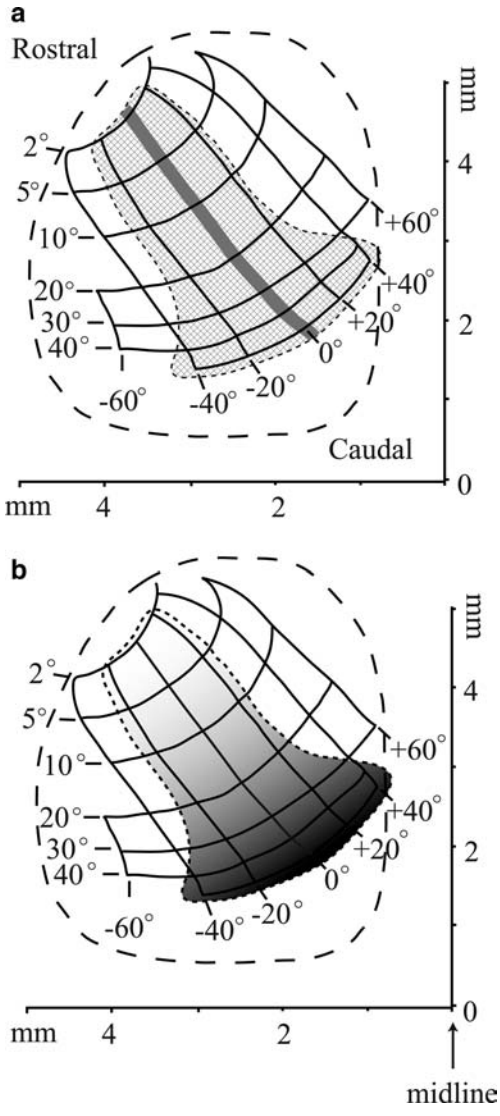

Fig. 9 Hypotheses for the generation of cMRF neuron open movement activity from activation of the superior colliculus. **a** In order to generate the open movement field activity observed in a subset of cMRF neurons a group of SC neurons along a horizontal meridian in the SC would need to be activated. In order to account for the variation in cMRF neuron movement field size as well as evidence of lack of sensitivity to the vertical component of movement, a larger swath of SC neurons would also be required to generate the cMRF movement field (*cross-hatching*). **b** A similar idea to that shown in **a**, but now there is a gradient of projections from the SC to the cMRF so that rostral SC neurons provide a much smaller contribution, while more caudal neurons would contribute a much higher number of projections or boutons to a single cMRF neuron. This arrangement would most likely generate the correct horizontal amplitude sensitivity. The collicular maps are modified from Robinson (1972)

monotonic increase in spike count with increasing head movement amplitude Fourth, eight postsaccadic neurons had monotonic relationships for head movements made to *either* side (i.e., the cells were bidirectional). Therefore, we conclude that their discharge was better associated with *head* rather than gaze movements. No neurons with these types of response characteristics associated with primate head movement have been reported previously.

Evidence of postsaccadic activity raises an interesting question: how could head movement fields be constructed and could the SC alone be the source of such activity? As already discussed above (Fig. 9a), neurons in the SC are topographically arranged such that neurons located in the caudal SC are associated with larger *gaze* shifts to the contralateral side. Graded contributions of either boutons or processes from the caudal SC to cMRF postsaccadic neurons could generate nearly linear movement field characteristics (presuming even efficacy of each bouton) (Fig. 9b). However, there are two problems with this idea when applying it to postsaccadic neurons. First, SC neurons are related to *gaze* rather than just *head* movements (Freedman and Sparks 1997a). Although the contribution of the head to gaze movements greater than 20° increases almost linearly with amplitude (Freedman and Sparks 1997a), increasing either the number of cells or boutons from the caudal portion of the SC to the cMRF could not generate a movement field whose activity was *solely* related to head movements. Second, we found that all postsaccadic cMRF neurons began to discharge after the onset of the gaze shift and their discharge continued following the end of the gaze shift. To date, no neurons responding after gaze shifts have been reported in the SC.

Another possibility is that the cMRF postsaccadic neurons are part of a descending cortico-reticulo-spinal network that is independent of input from the SC (Martinez-Trujillo et al. 2003; Peterson 2004). There are documented direct connections from the supplemental eye regions to the MRF (Shook et al. 1990) and the MRF has projections to the NRG in both the cat (Edwards 1975) and monkey (Cowie et al. 1994) as well as to the cervical spinal cord (Castiglioni et al. 1978). The relationship of postsaccadic cMRF neurons to head amplitude could support a role in descending motor control. Evidence that the same cervical musculature can be used to accelerate the head in one direction but decelerate head movements in the opposite direction (Corneil et al. 2001) would support a role for bidirectional neurons.

A third possibility, and the one that we favor, is that postsaccadic cMRF neurons represent a group of neurons whose discharge reflects aspects of the head movement that is in progress or has already occurred. This would agree with the latency measurements which demonstrated that the peak discharge of postsaccadic cMRF neurons occurs either just before or just after peak head velocity (Table 1 and Supplementary Electronic Table 2). In this scenario, postsaccadic cMRF neurons would form part of an updating mechanism within the core of the brainstem that provides feedback to higher structures of the amplitude and direction of the current movement of the head. This would agree with recent cMRF stimulation results which were able to stop or slow head movements (Waitzman et al. 2002). The

spatial characteristics of the postsaccadic cMRF neurons might be acquired from ascending projections arising from cells in the NRG which have been shown to be related head movements (Isa and Naito 1995; Sasaki et al. 1996) and project to the MRF (Cowie et al. 1994). The MRF projects to the NRTP (which has projections to the oculomotor portions of the cerebellar vermis), interstitial nucleus of Cajal, thalamus, and cerebral cortex (including the supplementary eye fields and the posterior parietal lobule), regions that require signals indicating changes in the position of the head (Edwards and de Olmos 1976; Klier et al. 2003).

Another possible role for feedback from the cMRF could be to cancel certain vestibular signals during head movements. The vestibular ocular reflex is suppressed during gaze shifts, but is completely functional by the end of the gaze shift as indicated by normal sensitivity of position vestibular pause neurons (Roy and Cullen 2002; Cullen et al. 2004). On the other hand the sensitivity of vestibular-only neurons remains attenuated throughout the duration of the head movement (Cullen et al. 2001). Therefore, the vestibular-only neurons must be suppressed during voluntary head movements (Peterson 2004). This suppression extends throughout the duration of the head movement (i.e., extending beyond the end of the gaze shift) and would correspond to the temporal and spatial characteristics of the postsaccadic cMRF neurons. Thus, as a group postsaccadic cMRF neurons could form an integral part of a reafference or corollary discharge system (Roy and Cullen 2004) that serves as a 'head movement estimator' (Peterson 2004). Another alternative would be that such postsaccadic activity could be directed to the head movement integrator proposed to maintain the posture of the head following head movements (Klier et al. 2002), which would require signals related to head shift amplitude analogous to the relationships we have observed in postsaccadic cMRF neurons. In any event, the postsaccadic neurons are unique and their role in head control will require further study.

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