Active Locomotion Increases Peak Firing Rates of Anterodorsal Thalamic Head Direction Cells

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Received 13 December 2000; accepted in final form 13 April 2001

Zugaro, Michaël B., Eiichi Tabuchi, Céline Fouquier, Alain Berthoz, and Sidney I. Wiener. Active locomotion increases peak firing rates of anterodorsal thalamic head direction cells. *J Neurophysiol* 86: 692–702, 2001. Head direction (HD) cells discharge selectively in macaques, rats, and mice when they orient their head in a specific ("preferred") direction. Preferred directions are influenced by visual cues as well as idiothetic self-motion cues derived from vestibular, proprioceptive, motor efferent copy, and command signals. To distinguish the relative importance of active locomotor signals, we compared HD cell response properties in 49 anterodorsal thalamic HD cells of six male Long-Evans rats during active displacements in a foraging task as well as during passive rotations. Since thalamic HD cells typically stop firing if the animals are tightly restrained, the rats were trained to remain immobile while drinking water distributed at intervals from a small reservoir at the center of a rotatable platform. The platform was rotated in a clockwise/counterclockwise oscillation to record directional responses in the stationary animals while the surrounding environmental cues remained stable. The peak rate of directional firing decreased by 27% on average during passive rotations ($r^2 = 0.73$, $P < 0.001$). Individual cells recorded in sequential sessions ($n = 8$) reliably showed comparable reductions in peak firing, but simultaneously recorded cells did not necessarily produce identical responses. All of the HD cells maintained the same preferred directions during passive rotations. These results are consistent with the hypothesis that the level of locomotor activity provides a state-dependent modulation of the response magnitude of AD HD cells. This could result from diffusely projecting neuromodulatory systems associated with motor state.

INTRODUCTION

Head direction (HD) cells discharge selectively when the head of the macaque, rat, or mouse is oriented in a specific direction in the horizontal plane, independent from location or ongoing behavior (Khabbaz et al. 2000; Ranck 1984; Robertson et al. 1999; reviews: Taube 1998; Taube et al. 1996). In rats, these neurons have been identified in the postsubiculum (PoS) (Taube et al. 1990a), the anterodorsal thalamic nucleus (AD) (Taube 1995), the dorsal striatum (Wiener 1993), the lateral dorsal thalamic nucleus (Mizumori and Williams 1993), the lateral mammillary nucleus (LMN) (Blair et al. 1998; Stackman and Taube 1998), and certain areas of parietal and retrosplenial cerebral cortices (Chen et al. 1994). The direction of maximal firing ("preferred direction") of the HD cells is strongly influenced by visual cues on the periphery (Goodridge and Taube 1995; Taube et al. 1990b; Zugaro et al. 2001). However, other sensory cues signaling changes in HD are also important since directional selectivity persists in total darkness (Blair and Sharp 1996; Chen et al. 1994; Mizumori and Williams 1993) and is abolished after lesions of the vestibular apparatus, even when visual cues are available (Stackman and Taube 1997). In experiments where visual landmarks and inertial signals provide conflicting information, preferred directions tend to recalibrate on visual cues, although inertial signals exert a small but significant influence (Knierim et al. 1998; Zugaro et al. 2000b). Altogether, the results indicate that both visual and self-motion cues are integrated in the elaboration of HD signals.

Several different sensory systems such as optokinetic, vestibular, visceral somatosensory, and proprioceptive can provide self-motion signals regardless of whether movements are active or passive, but locomotor command signals and motor efferent collateral information (combined with the proprioceptive feedback resulting from contact with the substrate) are absent in the case of passive displacements. How these respective signals are integrated in the HD system is not well understood. If rats are tightly wrapped in a towel and held firmly then rotated, the firing rates of the AD HD cells decrease to baseline firing levels (9 of 10 cells tested) (Taube 1995), while PoS HD cell firing rates decrease by 30% (7 of 9 cells tested) (Taube et al. 1990b). However, it is unclear whether this is due to the absence of active movement initiation cues or other factors related to restraint.

To better understand the influence of self-initiated motion cues on directional responses in AD HD cells, we recorded in unrestrained rats during both active displacements and passive rotations. The experiment was designed to avoid possible effects of stress or somatosensory stimulation due to restraining forces on the rats during passive rotations. For this the animals were trained to remain stationary with the muzzle above a reservoir (located in the center of the platform) that periodically delivered droplets of water. To sample a sufficient number of cell responses to generate directional response curves, the platform was rotated in clockwise/counterclockwise oscillations while the rat remained in place at the center and the cylinder on the periphery (Fig. 1) was maintained stable with

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respect to the experimental room (this was also repeated in the absence of the cylinder). These directional responses were then compared with those recorded from the same neurons during active foraging behavior.

Some of these data have been presented previously in abstract form (Zugaro et al. 2000a).

METHODS

Experimental subjects

Six male Long-Evans rats (200–250 g; CERJ, Le Genest-St-Isle, France) were water deprived and maintained at not <85% of normal body weight. This level of dehydration was necessary to motivate performance in the behavioral tasks, and the rats showed no obvious signs of distress (excessive grooming, hyper- or hypo-activity, aggressiveness). Animals were handled, weighed, and examined daily and, in case of the slightest indication of health problems, returned to ad libitum water and given veterinary treatment. In training and recording sessions, the rats were permitted to consume water until satiation and supplemental water was then provided ad libitum depending on body weight. Rats were permitted to rehydrate completely prior to each weekend. The animals were maintained on a 12 h light/12 h dark cycle in an approved animal facility. All animal care and experimental protocols were in accord with institutional and international standards, legal regulations (Certificat No. 7186, Ministère de l'Agriculture et de la Pêche) and the American Physiological Society policy regarding the use and care of animals.

Electrode implantation

The rats were implanted bilaterally with electrodes for recording in the AD. For four animals, the electrode bundles consisted of eight Formvar-coated nichrome wires (25 μm diam), while the other two received two tetrodes on each side (groups of 4 twisted nichrome wires insulated with polyethylene, 13 μm diam) (Recce and O'Keefe 1989). All electrode tips were gold-plated (200–800 kΩ impedance). Each pair of tetrodes or bundle of wires was inserted in a 30-gauge stainless steel cannula and mounted on one of two independently advanceable connector assemblies on a single headstage (Wiener 1993). Before surgery, the animals were tranquilized with xylazine, then deeply anesthetized with pentobarbital (40 mg/kg). The electrodes were implanted above the AD (AP -1.4 mm to -2.0 mm, ML ±1.1 mm to ±1.4 mm relative to Bregma, 4.2 mm ventral to brain surface) using conventional surgical techniques. The electrode descender assembly was permanently fixed to the skull with dental acrylic and seven tiny screws.

Behavioral apparatus

The 3 × 3 m square recording chamber was enclosed by a black canopy and black curtains suspended along four walls. The experimental apparatus (Fig. 1*A*) consisted of a black cylinder (60 cm high, 76 cm diam) with a white card (50 cm wide, covering 75° of arc) attached on the inner wall. This served as a salient visual landmark. The cylinder was placed on top of a platform with a small water reservoir located in the center. The water reservoir was a short (1 cm high) cylindrical block. This delivered drops of water from a slight conical depression at the top. A reserve of water was stored in an elevated bottle. A siphon tube transported the water to a computer-controlled solenoid valve outside the apparatus, then beneath the platform to the reservoir. The timing of the opening of the solenoid valves was directed and recorded by the data-acquisition system. The platform could be rotated independently while the cylinder was held fixed relative to the experimental room. Illumination was provided by a 40-W overhead lamp that diffused light evenly within the cylinder. The bright contrast of the lamp was intended to prevent the rats from viewing outside of the cylinder. All electronic instruments and computers were situated outside of the curtains, and the entire experimental room was phonically isolated from the rest of the building.

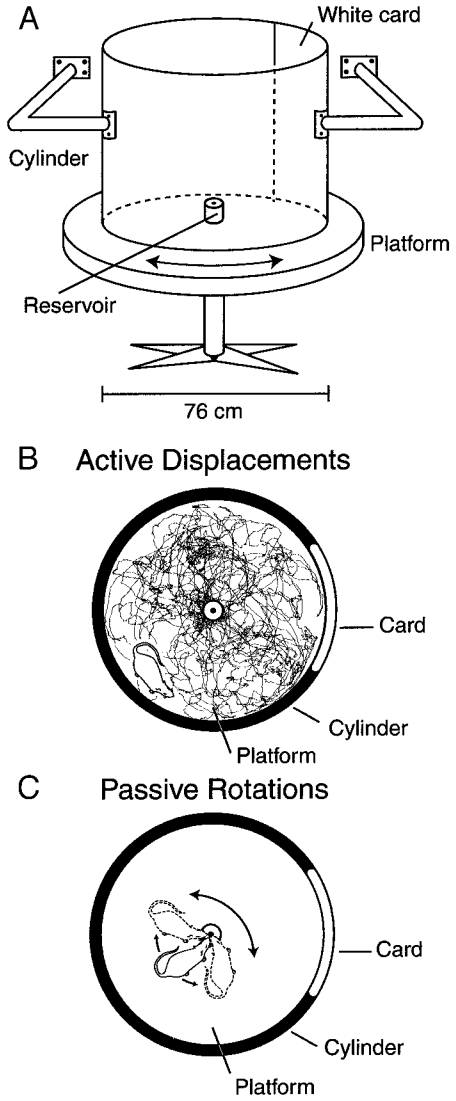

FIG. 1. *A*: the experimental apparatus. The cylinder was maintained stationary while the platform was rotated. The braces on the wall are schematic—actually an experimenter grasped the cylinder by a handle. During the active displacement phase (*B*, top view), the rat searched for food pellets (gray dotted line, trajectory). In the subsequent passive rotation phase (*C*, top view), the rat remained immobile while consuming water delivered at intervals at the center reservoir. In this phase the platform was rotated but the cylinder was maintained fixed relative to the room.

Behavioral tasks

Before the recording session was started, the experimenters estimated the preferred direction of the HD cell(s) by comparing the orientation of the freely moving rat (transmitted by an overhead camera and displayed on a monitor) with the amplified cell discharge signals from a loudspeaker. This was confirmed with the corresponding signals on an oscilloscope.

The recording sessions consisted in two phases. There was no interruption between the two phases, and thus the rat was not removed from the cylinder at any time during the experiment. In the baseline condition (*active displacements*), the rat moved freely within the arena for ≥5 min, foraging for and eating small food pellets (5 mg chocolate

sprinkles) thrown into the cylinder at pseudorandom locations by an experimenter (Muller et al. 1987); this task has also been previously used in studies of AD HD cells (Taube 1995). In this paradigm, well-trained rats visit most of the floor surface and show a fairly uniform distribution of head orientations over time (Fig. 1*B*).

The test phase (*passive rotations*) was conducted immediately before or after the active displacements phase. To motivate the rats to remain immobile at the center without physical restraint, they were trained to receive single drops of water (≈30 μl) at brief intervals (1–3 s) from the water reservoir (Fig. 1*C*). Water delivery was triggered manually either by keyboard presses that directed the computer to trigger opening of the solenoid valve or via the manual trigger of a signal generator. The transistor-transistor logic (TTL) signals were converted to 24 V to drive the solenoid valves. The only cues signaling the beginning of the passive rotations phase were the cessation of food distribution and the clicks of the solenoid valves. Water delivery was selectively timed to gently coax the rat to point its head in the preferred direction of the HD cell. While the rat was at the center, an experimenter manually rotated the platform in a clockwise/counterclockwise oscillation. Another experimenter held the cylinder stationary to keep the principal visual cues stationary relative to the experimental room. In this way, the head of the rat was passively rotated in and out of the preferred direction(s) that had been determined earlier. The amplitudes of the rotations were approximately 180°. In general the profiles were sinusoidal, and the maximum velocity ranged from 5 to 70°/s in different sessions. The central position of the reservoir ensured that the axis of rotation was centered on the head of the rat to minimize translational forces on the vestibular apparatus. The passive rotation phase of the recording session lasted from 5 to 15 min and was terminated when the rat was satiated and moved away from the reservoir.

In 8 sessions of 37 (in 3 of the 6 rats), the environmental setup was slightly different. The cylinder was absent during both the active displacements and passive rotations, and the rat could see the surrounding curtains along three walls as well as the electronic equipment along the fourth wall. In these experiments, the experimenter stood behind the rat while rotating the platform. These results were similar to those with the cylinder, and thus the data are considered together.

Data collection and unit isolation

Animals were brought into the recording room in a transparent plastic cage in the presence of orienting cues. Because the first recording session was conducted after the rats had experience within the cylinder for 6–18 days, the rats were familiar with the environment. The electrode channels were screened for HD cell activity while the rat explored freely and then performed the foraging task in the cylinder. If no supra-threshold HD cell activity was detectable, the electrodes were advanced slightly (25–50 μm). The electrode signals were checked again ≥4 h later. If HD cells were present, the platform was cleaned (if necessary) and the recording session began. Screening was conducted every working day.

During the recording sessions, electrode signals passed through field-effect transistors (FETs) were differentially amplified (10,000 times) and filtered (300 Hz to 5 kHz, notch at 50 Hz). The signal was then passed to a computer for automatic data collection. The acquisition software (DataWave Discovery, Longmont, CO) digitized and collected 32 voltage samples (from bundles of individual electrodes) or 128 voltage samples (from tetrodes) for each signal that crossed an experimenter-set threshold (sampling frequency ranged from 20 to 30 kHz). Single-unit activity was discriminated post hoc using "cluster-cutting" techniques based on at most eight different waveform parameters (maximum and minimum spike voltages, spike amplitude, time of occurrence of maximum and minimum spike voltages, spike duration, and 2 experimenter-defined voltage windows).

Prior to recordings, a support with two small lamps (10 cm separation) was mounted above the headstage. The positions of the two lamps were detected by a video camera mounted above the platform and a video tracking system (DataWave Technologies) that sampled at a rate of 60 Hz. After the end of the session, the heading direction of the animal in the horizontal plane was computed using the positions of the two lamps. C++ software (developed by M. B. Zugaro) scanned the position samples to automatically determine which lamp was rostral-most on the basis of displacement patterns (since the rats rarely walked backward). However, because tracking errors often produced ambiguous data, inversions of the lamps had to be further corrected with additional interactive software. Counter-clockwise rotations are considered positive here. Rotations of the platform were measured with a potentiometer and sampled by the acquisition system at 100 Hz.

Data analysis

HEAD DIRECTION. At each time step of data sampling, the orientation of the head of the rat was computed from the coordinates of the two head lamps sampled by the video tracking system. Because the arctangent operation required for this computation is sensitive to noise and jitter, before computing the heading directions the Cartesian coordinates of the two head lamps were smoothed by convolution with a Gaussian filter. Thus the smoothed abscissa of the front lamp was computed according to the following equation

$$X_{\text{front}}(t_i) = \frac{1}{N_i} \cdot \sum_{j=i-n/2}^{i+n/2} x_{\text{front}}(t_j) \cdot e^{-(t_j - t_i)^2/2\sigma^2}$$

where $X_{\text{front}}(t_i)$ is the smoothed abscissa of the front lamp at time t_i (in pixels), $x_{\text{front}}(t_j)$ is the raw abscissa of the front lamp at time t_j (in pixels), σ is the standard deviation of the Gaussian (in seconds), $(n + 1)$ is the range of the smoothing (in time steps of 1/60th of a second), and $N_i = \sum_{j=i-n/2}^{i+n/2} e^{-(t_j - t_i)^2/2\sigma^2}$ is a normalization factor. Here, we used $n = 10$ and $\sigma = nT/4 = 41.7$ ms (T is the sampling interval). This procedure was carried out independently for the abscissa and ordinate of the front and back lamps.

DIRECTIONAL RESPONSE CURVES. To determine the directional properties of the HD cells, the number of spikes was counted for each video sampling interval (1/60th of a second) and associated with the corresponding head orientation. This was used to compute a histogram wherein the magnitude of each 6° bin was the total number of action potentials divided by the time spent in that bin. A correction was made for the delay error of the data-acquisition system in the relative timing of video and cell discharge records.

For each HD cell in each recording session, an analytical approximation of the angular response curve was computed. This permitted reliable quantitative calculations of the preferred direction, peak firing rate, and angular range (a measure of the width of the directional response curve) for purposes of comparison. This curve fitting used a discretized adaptation of the Gaussian-like fit also used by Zhang (Johnson and Kotz 1970 as cited by Zhang 1996):

$$f(\theta) = A + B \cdot e^{K\cos(\theta - \theta_0)}$$

where $f(\theta)$ is the firing rate (in impulses/s), θ_0 is the preferred direction (in degrees), $B \cdot e^K$ is the peak firing rate (in impulses/s), $230°/\sqrt{K}$ is the angular range, and A is the baseline firing rate (in impulses/s). The angular range is computed as the distance between the two points at the intersection between the baseline firing rate line and the two tangent lines passing through the inflection points of the Gaussian-like curve (Zhang 1996). A best-fit (least-square distance) approximation to this curve was obtained with a Nelder-Mead type simplex search method via Matlab software (The MathWorks, Natick, MA).

ANGULAR AND LINEAR HEAD VELOCITIES. Angular head velocities were computed based on the general formula $\dot{\theta}(t) = X(t) \wedge X'(t)$. This describes the instantaneous angular velocity of a unit-length vector $X(t)$ as its vectorial product with its derivative vector. This method is preferable to the more intuitive differentiation of the instantaneous

heading angle because it overcomes the problem that instantaneous transitions from 0 to 360° are interpreted as very high angular velocities. Thus the vector series defined by the positions of the two lamps across time was smoothed (as described in the preceding text) and normalized as $X(t_i)$. Following classical numerical analysis methods, $X'(t_i)$ was approximated by filtering $X(t_i)$ with a Gaussian-derivative function (similar to the smoothing applied in the preceding text, except that the Gaussian function is replaced with its derivative and corrected with a minus sign). Angular head velocity was then computed as the vectorial product of $X(t_i)$ with $X'(t_i)$.

To compute linear head velocities, the Cartesian coordinates of the rostrally placed head lamp were differentiated (using the Gaussian-derivative smoothing explained above). This yielded linear velocity components along the x and y axes. The linear head velocities were then computed as the Euclidean norms of these velocity vectors. The latter analysis concerned only the position of the anterior lamp on the headstage since it was positioned directly over the head of the rat. If the anterior bulb was not in the central axis of rotation of the platform, this would give rise to measurements of lateral linear displacements. However, this is not likely to be a problem for the comparative analyses of passive and active rotations since this same ambiguity is present in both cases.

To avoid spurious results due to differences in the dynamics of active and passive rotations, analyses were also performed on subsets of data with comparable ranges of angular or linear head velocities. This reduced the number of samples taken into account, and sometimes the remaining data were suspected to be insufficient to compute reliable directional response curves. To determine whether the fit of the analytical approximation of the directional response curve was still adequate, an error function was computed

$$E = \frac{\sqrt{\sum (f(\theta_i) - f_i)^2}}{N \cdot \text{peak firing rate}}$$

where the numerator terms are the curve fit values and the actual measured values respectively (the sum is computed over the N bins falling within the angular range). Directional response data were discarded if this error was greater than 0.1 (this criterion was selected after subjective evaluation of a subset of the curves).

TEMPORAL PROPERTIES OF DISCHARGES. To investigate the temporal characteristics of the HD cell discharges, inter-spike interval histograms (ISIHs) were constructed (1 ms bins; range: 0–100 ms). To focus on discharge activity during maximal firing, this analysis

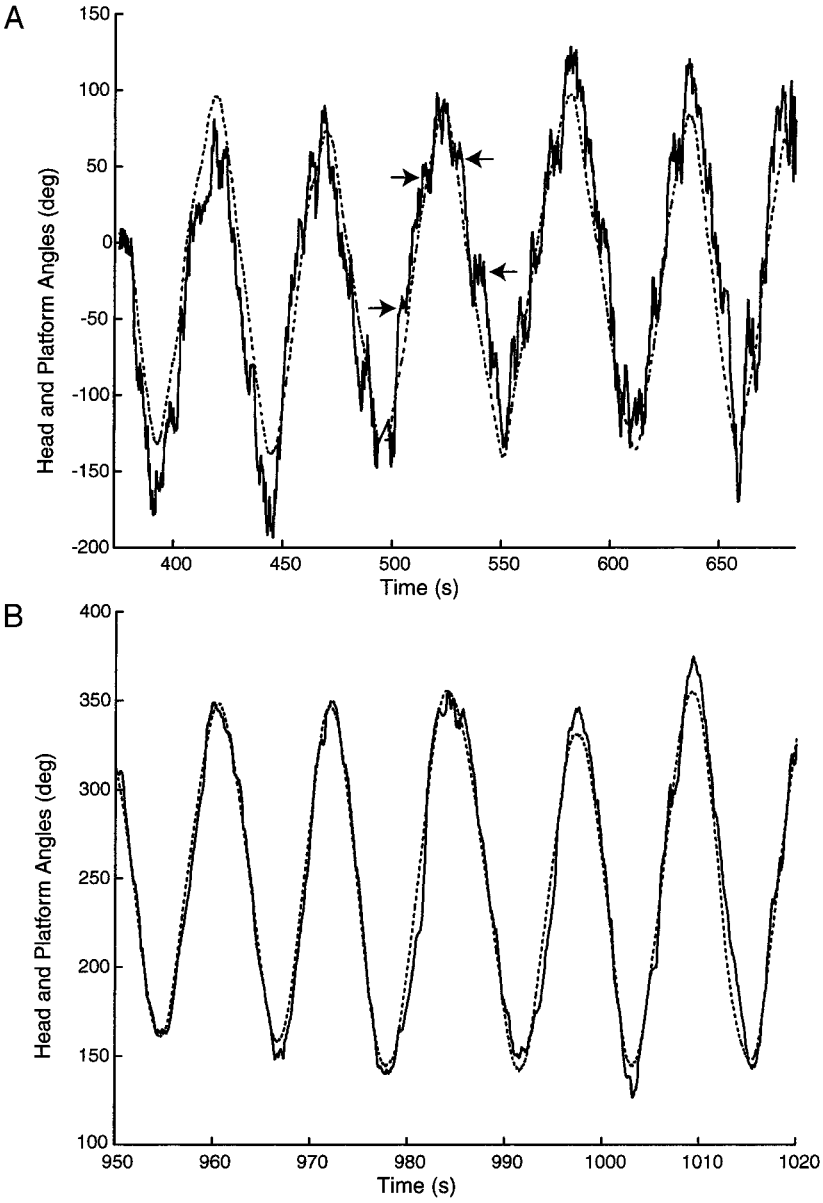

FIG. 2. Immobility of the rat during passive rotations. The angle of the platform relative to the room (- - -) as well as the angle of the head of the rat (—) are displayed in data from 2 different recording sessions with different time scales. *A*: slower rotations. The rat made a few active movements (→). *B*: more rapid rotations.

included only data recorded while the head of the rat was oriented in the preferred direction (± half a SD of the directional response curve ≈29°/$\sqrt{K}$). The data collected when the rat was oriented in this range were not necessarily sufficient to compute reliable ISIHs because some HD cells had low firing rates and the number of discharges was insufficient to produce a smooth curve or because in some sessions where several HD cells were recorded, those with preferred directions near the limit of the angular oscillations of the platform were not recorded for sufficiently long periods of time. Analysis of temporal patterns of discharge was based on data that produced fairly continuous ISIH plots (readily discernible by visual inspection). Statistical tests were performed using Statistica (StatSoft, Tulsa, OK) software or Microsoft Excel.

All the preceding computations were done by C++/MATLAB programs.

Histology

At the end of the experiments, a small electrolytic lesion was made by passing a small cathodal DC current (30 μA, 10 s) through one of the recording electrodes to mark the location of its tip. The rats were then lethally anesthetized with pentobarbital. Intracardial perfusion with saline was followed by 10% formalin-saline. Histological sections were stained with cresyl violet. Recording sites were reconstructed by detecting the small lesion, taking into account the distance that the microelectrode driver had been advanced from the point of stereotaxic placement of the electrodes.

RESULTS

Behavior

During the passive rotations, the rats tended to remain stationary; that is, the heading direction of the rats reliably followed the changes in orientation of the platform (Fig. 2). In Fig. 2*A*, the notches (→) on the traces of head direction correspond to small active counter-rotation movements. Since the rats consistently maintained their muzzles above the centrally placed water source, these movements were counterrotations of the body rather than rotations of the neck about a stable trunk. Thus this would not correspond to the vestibulocollic reflex (or head nystagmus). In contrast, in some cases, rats rotated their body increasing neck flexion angle during the onset of rotations while maintaining the head fixed at the same position over the water reservoir. In some cases, the rats would maintain this flexion during subsequent passive rotations. However, trunk position was not tracked by the video system. To quantify the degree of head immobility of the rats throughout the passive rotation sessions, measures of instantaneous directions of the head of the animal were tested for correlation with concurrent orientation of the platform. The average value of r computed from a group of typical sessions ($n = 17$) was 0.94 ± 0.01 (mean ± SE; range: 0.87–0.98). All r values were significant ($P < 0.001$).

Figure 3 shows the ranges of computed linear and angular velocities of the head during passive rotations and active displacements in a typical session. Although in the active displacement sessions there were more movements at rapid linear and angular velocities, the velocity incidence curves for active displacements and passive rotations had a considerable degree of overlap. Of course, the range of values in such angular velocity incidence curves varied among the passive rotation sessions, depending on the force applied to rotate the platform. The apparently elevated values of velocities during passive rotations might be due to small amplitude movements of the

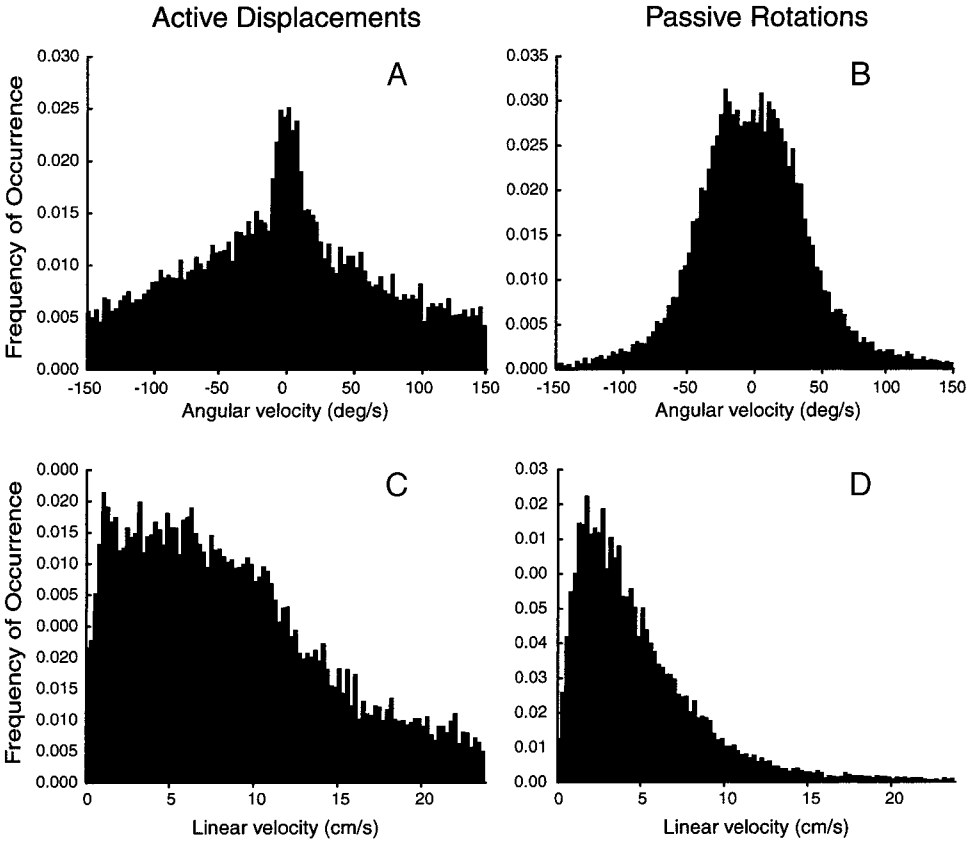

FIG. 3. Representative histograms of incidences of instantaneous angular head velocities during the active displacements (*A*) and passive rotations (*B*), all from 1 recording session (binwidth: 3°/s). Also shown are incidences of instantaneous linear velocities of the head during the active displacements (*C*) and passive rotations (*D*; binwidth: 0.24 cm/s).

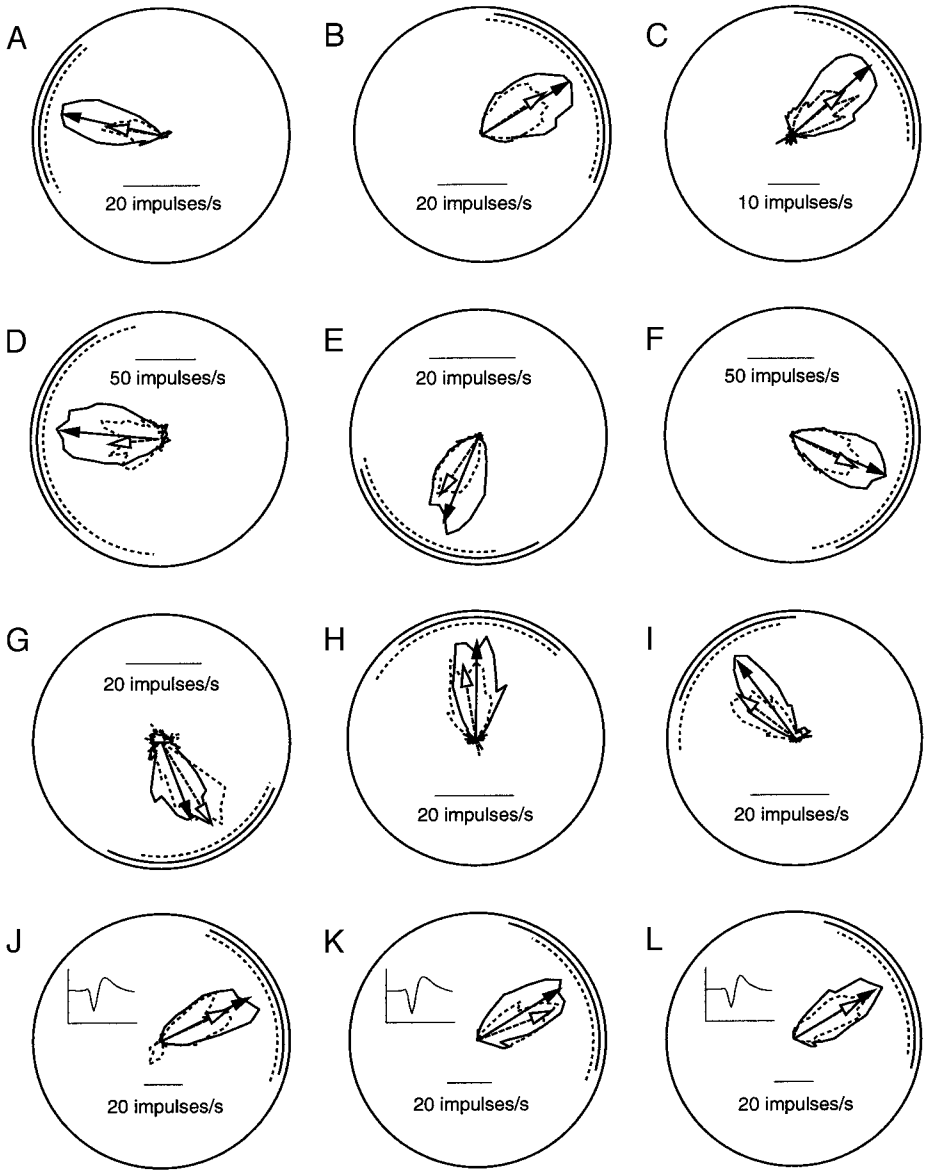

FIG. 4. Polar plots of directional response curves of 12 different HD cell recordings during active displacements (continuous lines) and passive rotations (dashed lines). The analytically computed preferred directions and peak firing rates are indicated by the directions and lengths of the arrows, respectively. Active displacements are indicated by continuous arrows and passive rotations by dashed arrows. Firing rate scales are shown in *insets* to each frame. The computed angular response ranges are represented as arcs (active displacements, continuous arcs; passive rotations, dashed arcs). In all cases the position of the cue card (not shown) was to the right as in Fig. 1. Cells shown in *G–I* were recorded simultaneously. Directional response curves *J–L* are from a single cell recorded on 3 different days (*insets*: waveforms are averages computed over 1,000 spikes; horizontal scale: 1 ms, vertical scale: 100 μV).

headstage lamps over very short time intervals or from slight head-bobbing movements observed while the rat was licking the water reservoir. Although these were small in amplitude, relatively high velocities would have been discriminated by the video detection system since the sampling rate was at 60 Hz. Jitter in video detection system could also have generated nonzero angular and linear velocities. Since each pixel corresponds to 0.3 cm, jumping one pixel in one sampling period would, for example, generate an instantaneous linear velocity of 18 cm/s. While this type of error was considerably reduced by the smoothing of the position data, it may not have been completely eliminated.

Overview of the cell response data

A total of 49 cells were recorded in the left (13 cells) and right AD (36 cells) of the six rats in 37 sessions. Eight cells were recorded in two or more sessions, yielding a total of 66 samples. Figure 4 shows 12 directional response curves computed for both active displacements (continuous lines) and passive rotations (dashed lines). The ovoid polar plots represent the actual response curves while arrows and concentric arcs concern parameters of the best fit analytic approximation. The peak firing rate (arrows) of most cells decreased markedly during passive rotations, but a few maintained the same value (e.g., Fig. 4*G*). In HD cells recorded in more than one session, similar decreases in firing rate were observed across sessions (Fig. 4, *J–L*). However, HD cells recorded simultaneously within a single session did not necessarily show the same reductions in peak firing rates during passive rotations. For example, Fig. 4, *G–I*, shows three cells recorded simultaneously: for two cells (Fig. 4, *H* and *I*), the peak firing rate decreased by 28 and 27%, respectively; but for the third cell (Fig. 4*G*), it increased by 11%. The ranges of the angular responses (dashed and continuous arcs) of the cells did not change consistently during passive rotations. In Fig. 4*D*, the angular response range increases; in Fig. 4*G*, it decreases. The HD cells generally maintained their preferred directions during passive rotations.

Peak firing rate reductions during passive rotations

The mean peak firing rate of the HD cells during the active displacements was 44 ± 3 (SE) impulses/s (range: 12–106 impulses/s) and 34 ± 2 impulses/s (range: 9–88 impulses/s) during the passive rotations. The peak firing rates were significantly reduced during the passive rotations (Wilcoxon matched pairs test, $n = 66$, $P < 0.001$).

To quantify the magnitude of this effect, Fig. 5 compares the peak firing rates measured during passive rotations and active displacements for each neuron. Previous results indicate that the discharge rate of the HD cells is higher when the rat moves at higher angular and linear velocities (Blair and Sharp 1995; Stackman and Taube 1997; Taube 1995; but see Taube and Muller 1998). To eliminate the risk that the reduced peak firing rates during passive rotations were due to the lower velocities in this condition, the data shown in Fig. 5 were computed based only on data where angular and linear head velocities were comparable in the two behavioral conditions ($\omega \leq 90°$/s and $v \leq 7.5$ cm/s). This did not affect the results: a linear regression analysis of the data in Fig. 5 showed that the firing rate of the HD cells decreased by 27% on average ($P < 0.001$) when the unrestrained rat was rotated passively. The magnitude of this reduction was not correlated with the value of the peak firing rate ($r = -0.12$, NS). During passive rotations, the peak firing rates decreased by more than 5% in 47/64 cases (73%), but increased by more than 5% in only 8 cases and remained constant for 9 cases (in 2 cases, there was insufficient data for this analysis; see METHODS).

VARIABLE RESPONSES OF SIMULTANEOUSLY RECORDED CELLS. Figures 4 and 5 show that there was some variability in the magnitude of the decreases in peak firing rates within the population of AD cells recorded. One possible reason for this might have been related to variations in the degree of immobility of the rats in the different sessions. As shown in Fig. 2, the rats tended to make active head movements slightly more frequently during passive rotations at lower velocities (Fig. 2*A*) than at higher velocities (Fig. 2*B*). We thus tested whether the change in peak firing rates was correlated with the degree of immobility of the rats during passive rotations in each recording session (measured by the correlation coefficient of the instantaneous head direction and instantaneous platform orientations; see *Behavior*). This showed no significant correlation ($r = -0.03$; NS).

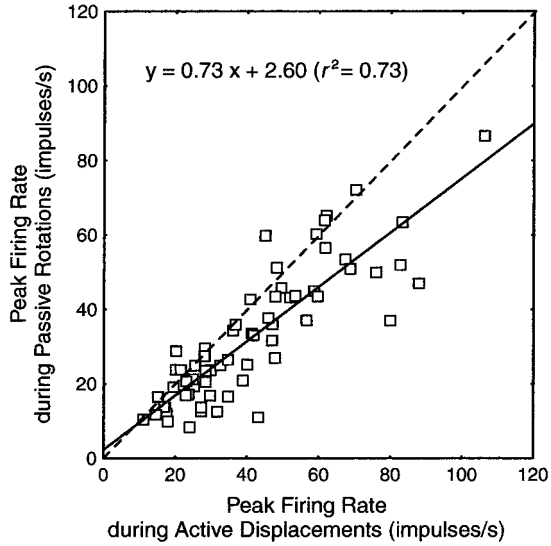

FIG. 5. Linear regression analysis of the peak firing rate of each neuron during passive rotations versus active displacements (slower movements). The equation of the regression line (continuous line) is shown *inset* above. Peak firing rates that remained the same during both conditions would fall on the dashed line.

Further evidence that inter-session variations in the behavioral parameters could not account for these fluctuations is that the magnitude of the decrease in peak firing rates varied among simultaneously recorded neurons (Fig. 4, *G–I*). This suggests that different HD cells may be affected differently by active locomotor signals. This is not likely to be simply due to random variation since, as reported below, in most cases when cells were recorded on successive days their responses did not vary. However, it is also possible that the differences in changes in peak firing rates were due to the fact that the oscillatory rotations of the platform oriented the head of the rat in the preferred directions of the cells at different phases of the cycle. Thus the activity of one cell may have been measured during movements with dynamics different from the others. To test for this, for each cell, the eccentricity of the preferred direction relative to the oscillatory rotations of the platform was determined. This was defined as the angular distance from the preferred direction to the center of the oscillations, divided by the half-amplitude of the oscillations. Thus a preferred direction near the center of the oscillations would yield an eccentricity close to 0, while a preferred direction near the edge would yield an eccentricity close to 1. A Pearson product-moment correlation failed to show a significant correlation between the eccentricities of preferred directions and reductions in peak firing rates of the HD cells ($r = 0.01$, $n = 66$; NS). This indicates that variations in movement dynamics cannot account for the different responses observed among simultaneously recorded cells.

RELIABILITY OF PEAK FIRING RATE REDUCTIONS. In several cases, the same HD cell was recorded from the same microelectrode during two or more consecutive sessions (2 sessions for 3 neurons; 3 sessions for 4 neurons, 1 of which is shown in Fig. 4, *J–L;* and 7 sessions for the remaining cell). Cell identification was based on visual inspection of waveforms (Fig. 4, *J–L*, *inset*) as well as the absence of marked differences in preferred direction and angular response range. Changes in peak firing rates during passive rotations were compared between successive recordings. This showed no significant difference between any of the sequential recordings (Wilcoxon matched pairs tests, $n = 17$; NS). Thus the responses were fairly consistent across recording sessions.

TEMPORAL CHARACTERISTICS OF CELL DISCHARGES DURING THE ACTIVE AND PASSIVE CONDITIONS. A possible basis for the peak firing rate decrease during passive rotations would be a lower overall level of excitation of the neurons leading to an increase in inter-spike intervals in this condition. Alternatively, changes in the temporal dynamics of the discharges could occur (e.g., due to changes in membrane properties of the neurons). To test for this, normalized inter-spike interval histograms (ISIHs) were constructed for those recordings with sufficient data (44 cases). As shown by the example in Fig. 6, there was little evidence for bursts in the discharges of the HD cells in either condition. The ISIHs shifted to the right (greater

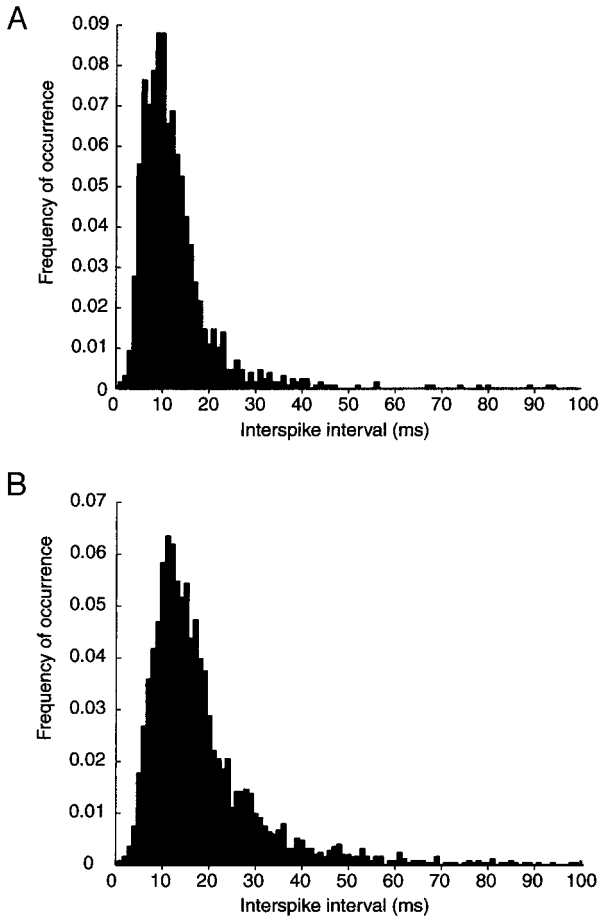

FIG. 6. Typical inter-spike interval histograms for a HD cell (shown in Fig. 4*F*) during active displacements (*A*) and passive rotations (*B*). The peak shifts to the right during passive rotations (the mean increases by 31%, coherent with the 34% reduction in peak firing rate). Bin widths are 1 ms; note that the *y* axes in *A* and *B* have different scales.

inter-spike intervals) during the passive rotations, resulting in greater medians (+29%), means (+25%), and modes (+25%) during the passive rotations. This shows that the observed decrease in peak firing rates is due to increased inter-spike intervals rather than to a change in temporal characteristics of the discharges.

ACTIVE LOCOMOTOR SIGNALS AND INERTIAL SIGNALS. As mentioned in the preceding text, several authors have reported an increase in firing rate during faster angular and linear head movements in freely moving rats (Blair and Sharp 1995; Stackman and Taube 1997; Taube 1995; but not Taube and Muller 1998). It is not known whether this results from stronger inertial (e.g., vestibular) signals, from active locomotor signals, or a combination of both. Because in our experiments the angular and linear head velocities and accelerations of the rats were more rapid during the active displacements (Fig. 3), it was necessary to determine whether this contributed to the difference in peak firing rates between active displacements and passive rotations.

To test for this, a repeated-measures ANOVA was conducted, where angular and linear head velocity levels were defined as independent factors. In addition, to compare data recorded during the active displacements and the passive rotations, movement type (active displacements vs. passive rotations) was considered a repeated measures factor. Angular velocity levels used for this analysis were $\omega \leq 30°/s$ and $30°/s < \omega \leq 90°/s$, while linear velocity levels were $v \leq 2.5$ cm/s, 2.5 cm/s $< v \leq 5$ cm/s, and 5 cm/s $< v \leq 7.5$ cm/s. Higher velocity data were discarded. The dependent variable was the increase in peak firing rate relative to the slowest movements ($\omega \leq 30°/s$ and $v \leq 2.5$ cm/s). The ANOVA showed a significant effect of movement type [$F(1,129) = 42.92$; $P < 0.001$]. All other factors, including interaction factors, were not significant. This indicates that, even for comparable angular and linear head velocity movements, the decrease in peak firing rate is not a secondary effect due to velocity dependence.

CONTROLLING FOR DIFFERENTIAL SHIFTS IN PREFERRED DIRECTIONS. Another possible explanation of the decrease in peak firing rate during passive rotations could have been that the preferred directions of the directional response curves had shifted by different angles during the clockwise and counterclockwise oscillations of the platform. In this case, the aggregate directional response curves computed in the preceding text would have lower peaks, although the individual clockwise or counterclockwise directional response curves would not show such a reduction. To test for this, data were separated into clockwise and counterclockwise oscillations during passive rotations, and peak firing rates were recomputed based on the new directional responses. This revealed that preferred directions were not significantly different between the clockwise and counterclockwise rotations (Wilcoxon matched pairs tests, $n = 66$, NS) Furthermore, peak firing rates during the clockwise and the counterclockwise passive rotations were each significantly lower than the peak rate computed for active displacements (Wilcoxon matched pairs tests, $n = 66$, $P < 0.001$). Therefore the decrease in peak firing rate during passive rotations is not due to the summation of offset response curves from the two directions of passive rotation.

TEST FOR RECORDING STABILITY. Small changes in the quality of isolation of extracellular recording signals can result in changes in measured firing rates. Because, in most sessions, active displacements were recorded before passive rotations, the decreases in peak firing rates observed here might have been due to electrode instability. Although this is an unlikely explanation for the systematic decreases in peak firing rates (cell isolation could also improve over time), an additional test was performed. Peak firing rates were compared between the first and second halves of the active displacements phase of the experiment. There was no significant difference between these measures (Wilcoxon matched-pairs test, $n = 66$, NS). Together with the fact that single cells recorded during successive days showed consistent decreases in peak firing rates across sessions (discussed in the preceding text), we conclude that variations in cell isolation do not account for the decrease in peak firing rates during passive rotations.

Preferred directions during the active displacements and passive rotations

The preferred direction of each HD cell was compared between active displacements and passive rotations. The mean absolute shift in preferred directions between the two conditions was 10 ± 1° (mean ± SE; range: −24 to +30°).

However, the preferred directions did not shift significantly clockwise or counterclockwise between the two conditions (Wilcoxon matched pairs test, $n = 66$; NS). This indicates that, on average, the HD cells maintained the same preferred directions when the animal was passively rotated (Fig. 7*A*).

Similar to the analysis conducted on peak firing rate decreases, the absolute shifts in preferred directions were tested for a correlation with the eccentricity of the preferred directions relative to the passive rotation oscillations. Again, this failed to show a significant correlation between the two variables (Pearson product-moment correlation, $r = 0.01$, $n = 66$; NS). This is consistent with the fact that the preferred directions of the HD cells are always updated in a coherent manner regardless of the dynamics of the passive movements.

Angular range of directional responses during the active displacements and passive rotations

The mean range of the directional responses of the HD cells during active displacements at all velocities was 98 ± 2° (range: 58–182°), while during passive rotations it was 107 ± 4° (range: 59–229°). The values measured during active displacements correspond to those of previous reports (Blair and Sharp 1996; Taube 1995). The angular ranges were not significantly different in the two conditions (Wilcoxon matched pairs tests, $n = 66$, NS; Fig. 7*B*).

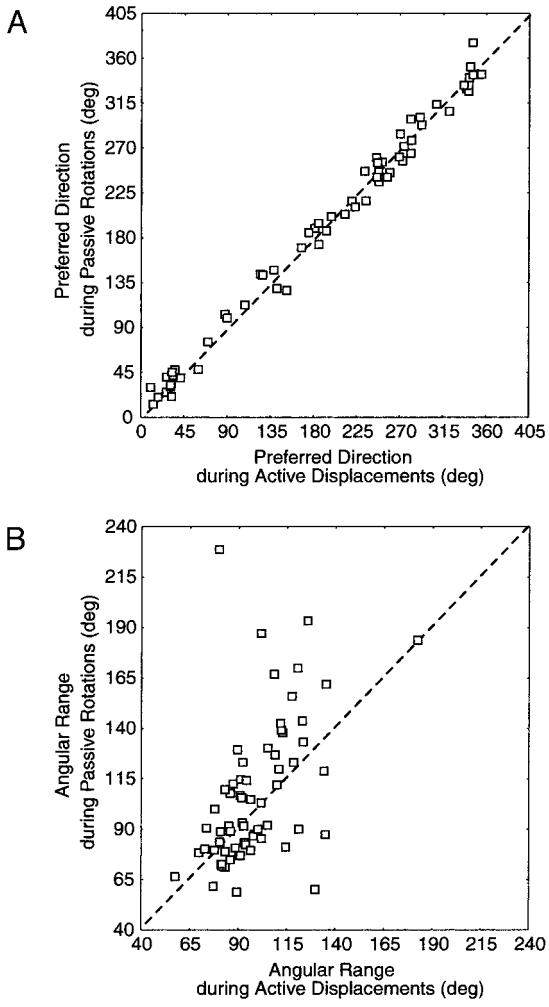

FIG. 7. Comparisons of the preferred directions (*A*) and angular response ranges (*B*) of the HD cells during passive rotations vs. active displacements. Dashed lines indicate values that remained the same during both conditions.

DISCUSSION

This study aimed to distinguish the respective contributions of active versus passive self-movement cues on directional signals in the AD. To do this, the directional responses of the same neurons were compared between active displacements and passive rotations in unrestrained animals. In the active displacement and the passive rotation phases of the present experiment, the preferred directions of the neurons did not change markedly. This indicates that the visual cues, as well as certain self-motion cues present in both conditions, were sufficient to establish and maintain this critical component of the directional signal. The 27% average decrease in peak firing rate during passive rotations is thus more likely to be due to those self-motion cues that were different in the passive and active conditions (discussed in the following text). In contrast, angular response ranges were not significantly different during the active displacements and the passive rotations. The implications of these results for understanding the generation and updating of thalamic head direction signals are discussed in the following sections.

Self-movement signals and AD HD cell activity

Several different self-motion cues could play a role in the reduction in peak firing rate from active displacements to passive rotations. Such cues could include the command signals for movement initiation, motor set (e.g., signals disinhibiting the subsequent activation of specific motor pathways), signals from efferent collaterals and corollary discharges of premotor and motor pathways proper, and the interaction of the latter with proprioceptive signals triggered by mechanical interactions with the substrate. Since the magnitude of the directional response increased when the rat made active movements, these results are consistent with the notion that the premotor and motor efferent collaterals (or corollary discharge) exert a state-dependent modulation of the AD HD signal. However, motor commands and motor set, while they were most likely different in the passive and active conditions, were still required in both cases. Remaining immobile in our passive condition also required the rats to exert forces to maintain postural equilibrium, resist rotational forces and inhibit movements of the head away from the water reservoir.

These observations suggesting that a state-dependent modulation of the AD HD signal is likely influenced by premotor and motor efferent collaterals, or corollary discharge, are consistent with the notion that head-direction information is critical during active locomotion and less so during nonlocomotor activities. The higher firing rates would thus convey more information to downstream structures (such as the hippocampus) during self-initiated movement than passive displacements.

Response suppression in HD cells and hippocampal place cells due to tight restraint

Taube (1995) found that when rats were tightly restrained, then rotated into the (previously determined) preferred direc-

tion, the directional responses were suppressed in 9 of 10 AD neurons, despite the continued presence of visual and inertial cues. In contrast, HD neurons of the postsubiculum, which is reciprocally connected to the AD (Van Groen and Wyss 1990, 1995), show decreases in firing rate by only 30% during tight restraint (Taube et al. 1990b). The degree of reduction in PoS HD cell discharges is proportional to the intensity of the restraint (E. J. Markus, personal communication) (cf. Markus et al. 1990). Chen et al. (1994) tested direction-selective neurons of retrosplenial cortical areas RSG and RSA in rats permitted to move freely, then passively rotated by 120–200° at 180–300°/s at regular intervals. For the latter, the rats were placed on a small elevated platform with 2 cm high barriers along the sides that restricted the movements, but not the view, of the animals. The majority of the neurons that showed significant direction selectivity during maze performance had little or no directional firing during the passive rotations.

Are peak firing rate reductions due to differences in vestibular inputs?

A recent electrophysiological study of the brain stem vestibular nuclei in monkeys (McCrea et al. 1999) showed that vestibular inputs are strongly attenuated during active head rotations. Vestibulo-spinal, and other non-eye-movement-related vestibular neurons that are sensitive to passive whole body rotations, showed firing suppression in most cases (73% of the 51 neurons recorded) during active head movements. In the remaining neurons, the discharge rate was attenuated by 20–75% during active head rotations. While the restraint and active movement conditions imposed on the monkeys were different from the present ones, these results suggest that vestibular neurons may have been more active in our rats during passive rotations than during the active displacements. Since the vestibular end organs are stimulated in both active and passive conditions, it is possible that movement initiation signals are responsible for the attenuation of vestibular neuron responses in the monkey experiments. However McCrea et al. (1999) suggest that the suppression of the vestibular signal would serve to inhibit the vestibulo-collic reflex during active movements. Thus during normal active turning movements, the head would turn with the body rather than reflexively turning toward the former direction. In our passively rotated rats, there was not convincing evidence for vestibulo-collic reflexes (Fig. 2), suggesting that such suppression was also present here (although it is not known whether the vestibular neurons with ascending projections are also inhibited during active movements). Thus following the above cited work, vestibular neuronal activity may have been attenuated both during the passive rotations and the active displacements of the rats in our experiment.

Can differences in motivational factors underlie peak firing rate reductions during passive rotations?

Because during the passive rotations the immobile animals were receiving droplets of water, while in the active displacements they received food, this difference may have contributed to the observed changes in peak firing rates. However, there is no evidence in previous studies for modulation of HD cell firings by ongoing behavior (for example, Dudchenko and Taube 1997). Furthermore, in both conditions the rats spent only a fraction of the time consuming rewards.

Are peak firing rate reductions during passive rotations associated with possible changes in hippocampal theta rhythmic slow activity (RSA)?

This question is motivated by the observation that place responses of hippocampal neurons are less specific during large-amplitude irregular (LIA) electroencephalogram than during theta RSA (Czurkó et al. 1999; Foster et al. 1989; Muller et al. 1987). However, there are indications that theta RSA was present during passive (as well as active) displacements. Theta RSA also occurs during passive rotations of restrained rats receiving periodic water rewards (Gavrilov et al. 1995, 1996). There was also no indication of rhythmic firing at theta frequencies in the inter-spike interval histograms, and there are no known direct projections from the theta-generating neurons of the nucleus of the diagonal band of Broca or from the hippocampus to the AD. In our view, it is more likely that other diffusely projecting neurotransmitter systems (perhaps also involved in the generation of theta RSA) might play a role in the firing rate reductions in the passive condition.

Serotonergic activity as a possible cause for firing reductions during passive rotations

The AD has one of the highest densities of 5-HT_7 receptor in the brain (Gustafson et al. 1996). In a review article, Jacobs and Fornal (1999) conclude that serotonergic neurons are activated in association with increased muscle tone and tonic motor activity. They interpreted this result within a theoretical framework where the serotonergic system plays an important role in facilitating motor output. In vitro, serotonin is known to regulate afterdepolarization of AD neurons (Chapin and Andrade 2000). Interestingly, AD receives serotonergic projections from the ventromedial and ventrolateral parts of the ipsilateral dorsal raphe, and to a lesser extent from the dorsomedial part of the nucleus, predominantly ipsilaterally, and the median raphe (Gonzalo-Ruiz et al. 1995). Altogether, this is consistent with the hypothesis that serotonergic mechanisms may be responsible for higher peak firing rates in AD neurons during active locomotion than passive displacements. If this is the case, such a mechanism could also mediate the suppression of place cell activity in hippocampal neurons of tightly restrained rats (Foster et al. 1989) since there is also a high 5-HT_7 receptor density there.

We thank Drs. R. Andrade, H. T. Blair, J. Droulez, P. E. Sharp, and J. S. Taube for valuable discussions; Dr. R. Lestienne for help in temporal analyses of neuronal discharges; Drs. N. Brunel and I. Israël for comments on the text; J. Cote for help in data analysis; M.-A. Thomas and N. Quenech'du for histology; A. Treffel, M. Ehrette, and S. Ilic for the construction of the behavioral apparatus; P. Leboucher for electronic equipment; F. Maloumian for illustrations; and S. Lemarchand and D. Raballand for animal care. E. Tabuchi was on leave from the Dept. of Physiology, Toyama Medical and Pharmacological University, Toyama, Japan.

This work was supported by Centre National de la Recherche Scientifique-National Science Foundation cooperation, Centre National d'Etudes Spatiales, Cogniseine, Groupement d'Intérêt Scientifique. M. B. Zugaro received a grant from the Fondation pour la Recherche Médicale.

REFERENCES

BLAIR HT, CHO J, AND SHARP PE. Role of the lateral mammillary nucleus in the rat head direction circuit: a combined single unit recording and lesion study. *Neuron* 21: 1387–1397, 1998.

BLAIR HT AND SHARP PE. Anticipatory head direction signals in anterior thalamus: evidence for a thalamocortical circuit that integrates angular head motion to compute head direction. *J Neurosci* 15: 6260–6270, 1995.

BLAIR HT AND SHARP PE. Visual and vestibular influences on head-direction cells in the anterior thalamus of the rat. *Behav Neurosci* 110: 643–660, 1996.

CHAPIN EM AND ANDRADE R. Calcium-independent afterdepolarization regulated by serotonin in anterior thalamus. *J Neurophysiol* 83: 3173–3176, 2000.

CHEN LL, LIN L-H, GREEN EJ, BARNES CA, AND MCNAUGHTON BL. Head-direction cells in the rat posterior cortex. I. Anatomical distribution and behavioral modulation. *Exp Brain Res* 101: 8–23, 1994.

CZURKÓ A, HIRASE H, CSICSVARI J, AND BUZSÁKI G. Sustained activation of hippocampal pyramidal cells by 'space clamping' in a running wheel. *Eur J Neurosci* 11: 4373–4380, 1999.

DUDCHENKO PA AND TAUBE JS. Correlation between head direction cell activity and spatial behavior on a radial arm maze. *Behav Neurosci* 111: 3–19, 1997.

FOSTER TC, CASTRO CA, AND MCNAUGHTON BL. Spatial selectivity of rat hippocampal neurons: dependence on preparedness for movement. *Science* 244: 1580–1582, 1989.

GAVRILOV V, WIENER SI, AND BERTHOZ A. Enhanced hippocampal theta EEG during whole body rotations in awake restrained rats. *Neurosci Lett* 197: 239–241, 1995.

GAVRILOV V, WIENER SI, AND BERTHOZ A. Whole-body rotations enhance hippocampal theta rhythmic slow activity in awake rats passively transported on a mobile robot. *Ann NY Acad Sci* 781: 385–398, 1996.

GONZALO-RUIZ A, LIEBERMAN AR, AND SANZ-ANQUELA JM. Organization of serotoninergic projections from the raphé nuclei to the anterior thalamic nuclei in the rat: a combined retrograde tracing and 5-HT immunohistochemical study. *J Chem Neuroanat* 8: 103–115, 1995.

GOODRIDGE JP AND TAUBE JS. Preferential use of the landmark navigational system by head direction cells in rats. *Behav Neurosci* 109: 1–12, 1995.

GUSTAFSON EL, DURKIN MM, BARD JA, ZGOMBICK J, AND BRANCHEK TA. A receptor autoradiographic and in situ hybridization analysis of the distribution of the 5-HT_7 receptor in rat brain. *Br J Pharmacol* 117: 657–666, 1996.

JACOBS BL AND FORNAL CA. Activity of serotonergic neurons in behaving animals. *Neuropsychopharmacology* 21: 9S–15S, 1999.

JOHNSON NL AND KOTZ S. *Continuous Univariate Distributions*. New York: Wiley, 1970, vol. 2.

KHABBAZ A, FEE MS, TSIEN JZ, AND TANK DW. A compact converging-electrode microdrive for recording head direction cells in mice. *Soc Neurosci Abstr* 26: 984, 2000.

KNIERIM JJ, KUDRIMOTI HS, AND MCNAUGHTON BL. Interactions between idiothetic cues and external landmarks in the control of place cells and head direction cells. *J Neurophysiol* 80: 425–446, 1998.

MARKUS EJ, MCNAUGHTON BL, BARNES CA, GREEN JC, AND MELTZER J. Head direction cells in the dorsal presubiculum integrate both visual and angular velocity information. *Soc Neurosci Abstr* 16: 441, 1990.

MCCREA RA, GDOWSKI GT, BOYLE R, AND BELTON T. Firing behavior of vestibular neurons during active and passive head movements: vestibulospinal and other non-eye-related neurons. *J Neurophysiol* 22: 3077–3099, 1999.

MIZUMORI SJY AND WILLIAMS JD. Directionally selective mnemonic properties of neurons in the lateral dorsal nucleus of the thalamus of rats. *J Neurosci* 13: 4015–4028, 1993.

MULLER RU, KUBIE JL, AND RANCK JB JR. Spatial firing patterns of hippocampal complex-spike cells in a fixed environment. *J Neurosci* 7: 1935–1950, 1987.

RANCK JB JR. Head-direction cells in the deep cell layers of dorsal presubiculum in freely moving rats. *Soc Neurosci Abstr* 10: 599, 1984.

RECCE M AND O'KEEFE J. The tetrode: a new technique for multi-unit extracellular recording. *Soc Neurosci Abstr* 19: 1250, 1989.

ROBERTSON RG, ROLLS ET, GEORGES-FRANÇOIS P, AND PANZERI S. Head direction cells in the primate pre-subiculum. *Hippocampus* 9: 206–219, 1999.

STACKMAN RW AND TAUBE JS. Firing properties of head direction cells in the rat anterior thalamic nucleus: dependance on vestibular input. *J Neurosci* 17: 4349–4358, 1997.

STACKMAN RW AND TAUBE JS. Firing properties of rat lateral mammillary single units: head direction, head pitch, and head angular velocity. *J Neurosci* 18: 9020–9037, 1998.

TAUBE JS. Head direction cells recorded in the anterior thalamic nuclei of freely moving rats. *J Neurosci* 15: 70–86, 1995.

TAUBE JS. Head direction cells and the neurophysiological basis for a sense of direction. *Prog Neurobiol* 55: 1–32, 1998.

TAUBE JS, GOODRIDGE JP, GOLOB EJ, DUDCHENKO PA, AND STACKMAN RW. Processing the head direction cell signal: a review and commentary. *Brain Res Bull* 40: 477–486, 1996.

TAUBE JS AND MULLER RU. Comparisons of head direction cell activity in the postsubiculum and anterior thalamus of freely moving rats. *Hippocampus* 8: 87–108, 1998.

TAUBE JS, MULLER RU, AND RANCK JB JR. Head-direction cells recorded from the postsubiculum in freely moving rats. II. Effects of environmental manipulations. *J Neurosci* 10: 436–447, 1990a.

TAUBE JS, MULLER RU, AND RANCK JB JR. Head-direction cells recorded from the postsubiculum in freely moving rats. I. Description and quantitative analysis. *J Neurosci* 10: 420–435, 1990b.

VAN GROEN T AND WYSS JM. The postsubicular cortex in the rat: characterization of the fourth region of the subicular cortex and its connections. *Brain Res* 529: 165–177, 1990.

VAN GROEN T AND WYSS JM. Projections of the anterodorsal and anteroventral nucleus of the thalamus to the limbic cortex in the rat. *J Comp Neurol* 358: 584–604, 1995.

WIENER SI. Spatial and behavioral correlates of striatal neurons in rats performing a self-initiated navigation task. *J Neurosci* 13: 3802–3817, 1993.

ZHANG K. Representation of spatial orientation by the intrinsic dynamics of the head-direction ensemble: a theory. *J Neurosci* 16: 2112–2126, 1996.

ZUGARO MB, BERTHOZ A, AND WIENER SI. Background, but not foreground, spatial cues are taken as references for head direction responses by rat anterodorsal thalamus neurons. *J Neurosci* 21: RC154(1–5), 2001.

ZUGARO MB, TABUCHI E, FOUQUIER CF, BERTHOZ A, AND WIENER SI. Peak firing rates of anterodorsal thalamic head direction cells decrease during passive rotations in rats trained to remain immobile while unrestrained. *Soc Neurosci Abstr* 26: 984, 2000a.

ZUGARO MB, TABUCHI E, AND WIENER SI. Influence of conflicting visual, inertial and substratal cues on head direction cell activity. *Exp Brain Res* 133: 198–208, 2000b.