THE BRAINSTEM SWITCH FOR GAZE SHIFTS IN HUMANS

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***Abstract* – Saccades are rapid eye movements that turn both eyes in the same direction. Brainstem omnipause neurons gate saccades. Most natural shifts of the fixation point are between targets lying in different directions and at different distances requiring a combination of saccades and vergence. We investigated whether the visual stimulus, the saccadic command or the vergence command turns off omnipause neurons during gaze shifts. Using the scleral search coil technique, eye movements were measured in seven normal subjects, as they made voluntary, disjunctive gaze shifts comprising saccades and vergence movements. Conjugate oscillations of small amplitude and high frequency were identified during the vergence movement that followed the initial saccade. These oscillations, which are an indication that the omnipause neurons are turned off, corresponded to the saccade onset, and not the vergence eye movement or the visual stimulus. These data were used to test and modify a model of the human saccade-vergence system.**
***Keywords* – Eye movements, binocular, vergence, prediction**

I. Introduction

A prerequisite for clear binocular vision is that the fovea of each eye, which contains the highest density of photoreceptors, be pointed at the object of regard. Under natural conditions, most shifts of our point of visual fixation are between objects that lie in different directions and different distances in the environment. The ability to move the point of binocular fixation from one target to another is achieved by two distinct types of eye movements – saccades and vergence [1].

Voluntary shifts of the angle of gaze between objects located in different directions are achieved by saccades – rapid eye movements that carry the eyes in the same direction (versional or conjugate movements). Voluntary shifts of the point of fixation between objects lying at different depths in the environment require vergence movements, during which the eyes rotate in opposite directions (disjunctive rotations). Saccades take less than 100 ms for completion whereas vergence movements may require several seconds. Saccades and vergence movements are generated by separate populations of "burst neurons," which lie in the brainstem [2,3].

Saccadic burst neurons are inhibited by omnipause neurons, which lie in the pons of the brainstem [4]. Electrical stimulation of omnipause neurons stops saccades in mid-flight [5]. Recent studies have suggested that omnipause neurons gate both saccadic and vergence burst neurons, and thus act as a premotor switch that allows gaze-shifts [6,7]. Omnipause neurons receive motor commands from the frontal eye fields and the superior colliculus [8], and also respond to visual stimuli [9]. In this study, we investigated whether it was the visual stimulus, the saccadic command, or the vergence command that triggered the omnipause "switch" to permit a shift in the point of fixation (Fig. 1). Our experimental strategy was to look for small, high-frequency oscillations, which are a behavioral marker that the omnipause neurons are turned off [1]. We used our data to test predictions of a current model for combined saccade-vergence movements.

II. Methods

We studied seven normal subjects, all of whom gave informed consent. The study was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by our Institutional Review Board.

We measured horizontal and vertical movements of each eye using the magnetic search-coil technique, with 6-foot field coils that used a rotating magnetic field in the horizontal plane and an alternating magnetic field in the vertical plane. Search coils were calibrated before each experimental session. The system was 98.5% linear over an operating range of ± 20°, the SD of system noise was less than 0.02° and cross talk between horizontal and vertical channels was less than 2.5%.

Subjects alternately switched their point of fixation between near and far targets, both aligned on their midlines. The far visual stimulus was a red laser spot at 1.2 m, and the near target was a green LED at either ~15 cm or ~25 cm. Each target was alternately illuminated in a predictable sequence, every 1.25 s.

To avoid aliasing, coil signals were passed through Krohn-Hite Butterworth filters (bandwidth 0-150 Hz) before digitization at 500 Hz with 16-bit resolution. These digitized coil signals were filtered with an 80-point software filter (Remez FIR, bandwidth 0-100 Hz). The Remez filter is applied twice, forward and backward, so as to cancel out the phase shift. Also, any oscillations introduced by the filtering operation is symmetrical, and application of the filter in both directions would eliminate these. We compared original and filtered signals of eye position and velocity, and detected no attenuation or phase shift. Eye velocity was obtained using a four-point differentiator based on a least-squares procedure that produced similar peak values to, but introduced less noise than, a simple two-point differentiation algorithm [1]. With this differentiator and a digitization frequency of 500 Hz, the bandwidth of the first derivative was 0 to 148 Hz. Recording from a search coil fixed to a stationary mounting, using this differentiator, the overall system noise had an SD of less than 1.0°/s for velocity. All

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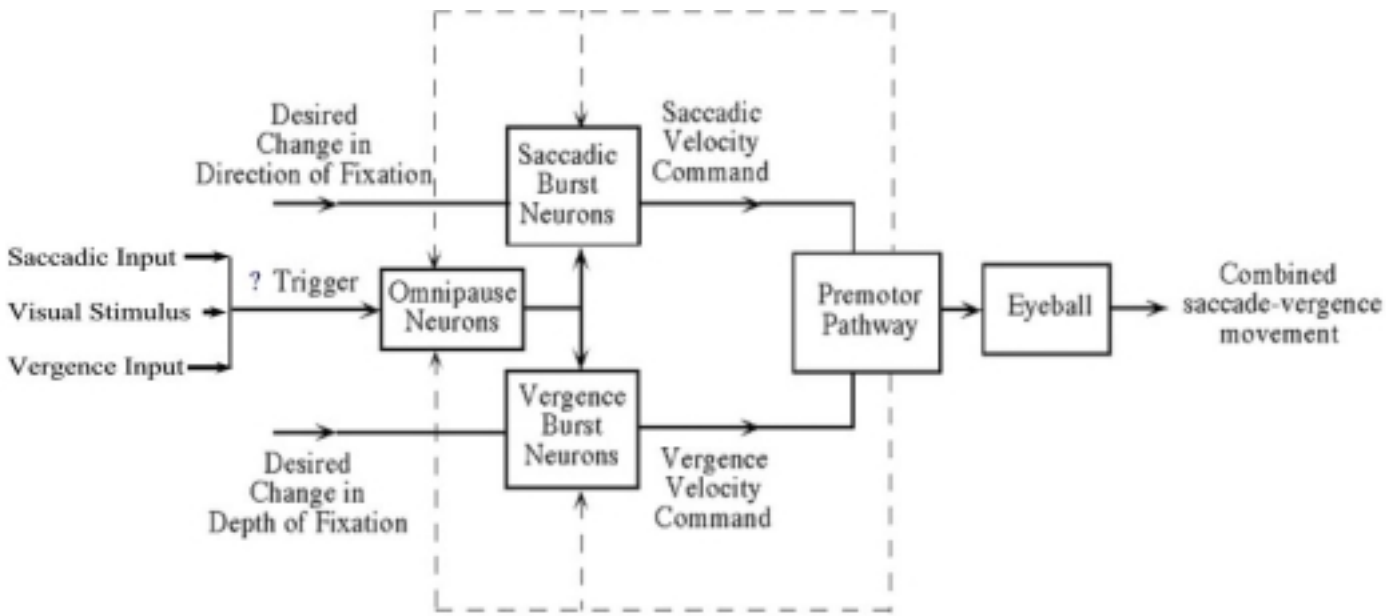

Fig. 1. A schematic showing the possible trigger signals to the omnipause neurons that in turn gate the saccadic and vergence burst neurons to make the eyeball execute a combined saccade-vergence movement.

responses were analyzed interactively, with particular attention to responses that preceded the stimulus jump (predictive responses).

III. Results

All subjects showed some anticipatory responses, each consisting of a vergence drift, accompanied by a small saccade, that preceded target jumps. Overall, predictive responses occurred during 95% of divergence and 85% of convergence movements. In all trials, an initial vergence movement preceded the saccade, and this was always free of high-frequency oscillations. At the onset of the saccadic component, conjugate oscillations at around 30 Hz commenced, and these were sustained during the part of the vergence movement that continued after the saccade was completed (Fig. 2A). High-frequency oscillations were consistently absent before the saccade, but often commenced before the visual stimulus jumped.

IV. Discussion

Referring to the experimental questions summarized in Fig. 1: High-frequency conjugate oscillations, which indicate that omnipause neurons were switched off, never occurred during the vergence movement that preceded the saccade; they always commenced after the initial saccade, and they occurred during anticipatory responses (before the visual target jumped to its new position). Thus, these results indicate that the saccadic command causes omnipause neurons to be turned off, not the vergence command and not the visual stimulus for the gaze shift.

Tests Of A Saccade-Vergence Model

We used the present data to test a current model for saccade-vergence interactions, described by Zee and colleagues [7]. To simulate the vergence-saccade pattern that we observed, we implemented this model using MATLAB/SIMULINK, and presented the saccadic command 10 ms after the vergence component. We did not attempt to simulate the presaccadic vergence response nor did we allow an interaction between vergence and saccadic burst neurons. Our focus of interest was whether conjugate oscillations, such as we observed (Fig 2A), were generated by the model, since these are the behavioral marker for the brainstem saccadic switch. We found that to produce these oscillations (Fig. 2B), we needed to increase the gain of saccadic burst neurons for small movements. This result suggests that the gain of the saccadic system for small motor errors (desired change in direction of fixation – Fig. 1) is larger than Zee and colleagues suggested, and that if omnipause neurons are turned off, but no saccadic command is present (after the saccade), then small conjugate oscillations at about 30Hz occur. Some normal subjects can voluntarily induce these oscillations using a vergence effort (“voluntary nystagmus”) [10]. Our data indicated that a small saccade is needed to turn off the omnipause switch and that a high gain of burst neurons is required to sustain the oscillations.

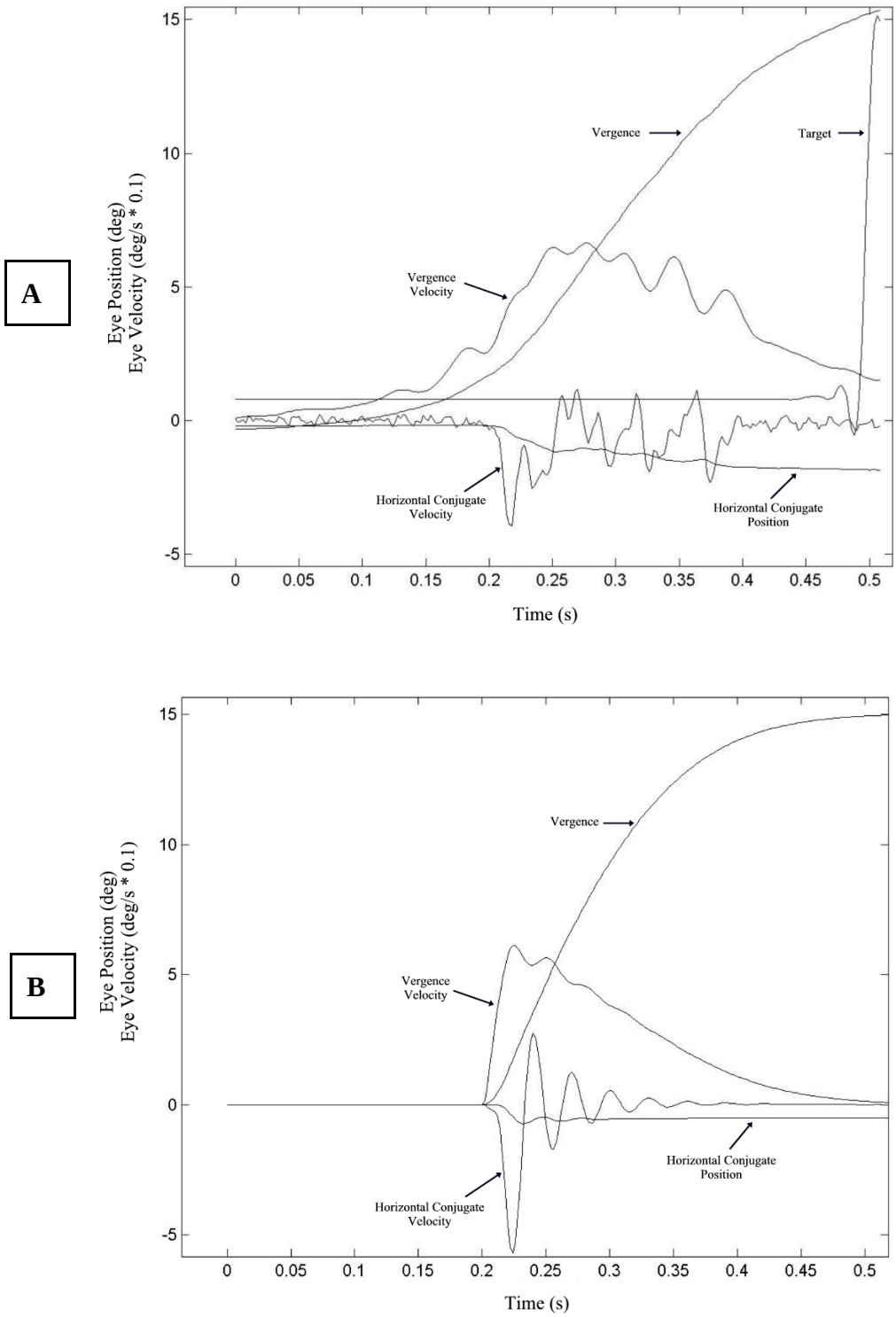

Fig. 2. (A) Representative records of individual responses when one subject shifted the fixation point from the far target to the near target (convergence). The targets were aligned on the subjects' midlines. The target motion, vergence movement, version movement, the vergence velocity, and the version velocity are plotted. (B) Results from the simulation of the saccade-vergence model by Zee and colleagues. To produce the conjugate oscillations, we needed to increase the gain of the saccadic burst neurons. We did not attempt to simulate the anticipatory vergence drift before the occurrence of the saccade. In both plots, note different scales for eye position and eye velocity.

V. Conclusion

We have shown that a behavior marker of a brainstem motor switch can be used to detect the nature of the sensory and motor commands that drive ballistic eye movements. Our data suggest a modification to a current model that accounts for combined saccade-vergence shifts of the point of fixation.

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