Perturbation of Combined Saccade-Vergence Movements by Microstimulation in Monkey Superior Colliculus

VIVEK CHATURVEDI AND JAN A. M. VAN GISBERGEN
Department of Medical Physics and Biophysics, University of Nijmegen, 6500 HB Nijmegen, The Netherlands

Chaturvedi, Vivek and Jan A. M. Van Gisbergen. Perturbation of combined saccade-vergence movements by microstimulation in monkey superior colliculus. *J. Neurophysiol.* 81: 2279–2296, 1999. This study investigated the role of the monkey superior colliculus (SC) in the control of visually (V)-guided combined saccade-vergence movements by assessing the perturbing effects of microstimulation. We elicited an electrical saccade (E) by stimulation (in 20% of trials) in the SC while the monkey was preparing a V-guided movement to a near target. The target was aligned such that E- and V-induced saccades had similar amplitudes but different directions and such that V-induced saccades had a significant vergence component (saccades to a near target). The onset of the E-stimulus was varied from immediately after V-target onset to after V-saccade onset. E-control trials, where stimulation was applied during fixation of a V-target, yielded the expected saccade but no vergence. By contrast, early perturbation trials, where the E-stimulus was applied soon after the onset of the V-target, caused an E-triggered response with a clear vergence component toward the V-target. Midflight perturbation, timed to occur just after the monkey initiated the movement toward the target, markedly curtailed the ongoing vergence component during the saccade. Examination of pooled responses from both types of perturbation trials showed weighted-averaging effects between E- and V-stimuli in both saccade and fast vergence components. Both components exhibited a progression from E- to V-dominance as the E-stimulus was delayed further. This study shows that artificial intervention in the SC, while a three-dimensional (3D) refixation is being prepared or is ongoing, can affect the timing (WHEN) and the metric specification (WHERE) of both saccades and vergence. To explain this we interpret the absence of overt vergence in the E-controls as being caused by a zero-vergence change command rather than reflecting the mere absence of a collicular vergence signal. In the perturbation trials, the E-evoked zero-vergence signal competes with the V-initiated saccade-vergence signal, thereby giving rise to a compromised 3D response. This effect would be expected if the population of movement cells at each SC site is tuned in 3D, combining the well-known topographical code for direction and amplitude with a nontopographical depth representation. On E-stimulation, the local population would yield a net saccade signal caused by the topography, but the cells coding for different depths would be excited equally, causing the vergence change to be zero.

INTRODUCTION

This study was designed to investigate the involvement of the monkey superior colliculus (SC) in binocular refixations to targets in three-dimensional (3D) visual (V)-space requiring combined saccade-vergence responses. It is well known from previous electrophysiological studies that the SC is involved in the control of saccades (for review see Sparks and Mays 1980; Wurtz 1996) through its connections with saccadic burst cells (see Munoz and Wurtz 1995; Sparks 1978) and its association with the omnipause neurons (OPNs) in the brain stem (Buttner-Ennever and Horn 1994; Gandhi and Keller 1997; Raybourn and Keller 1977). In contrast relatively little is known about the neuronal circuitry controlling vergence movements at the premotor and higher levels. This has made it rather difficult to understand the neural mechanisms controlling eye movements that are composed of both directional and depth components. An early suggestion by Yarbus (1967) was that the saccadic and vergence systems function rather independently of each other. Investigators long had the tendency to study each oculomotor subsystem in isolation from the other and the finding that saccade and vergence responses have strongly contrasting dynamics lent some credibility to the Yarbus concept. Early modeling studies (for overview see Collewijn et al. 1995), by emphasizing these distinctions, helped reinforce the conviction that the two systems are quite different in nature. It is commonly accepted that the saccadic system (classically defined as the system that causes the eyes to move equally in the same direction to fixate a target of interest in the frontal plane) does not process its inputs continuously. The saccadic system is normally suppressed by tonic pause cell activity that must be inhibited before a saccade can be made (gating). Saccadic eye movements are much too fast to allow sensory feedback during the movement. In contrast to this intermittent behavior, however, the vergence system (which moves the eyes in opposite directions in the horizontal plane to maintain binocular alignment when gaze is shifted between targets at different distances) was often portrayed as a continuous system relying on V-feedback.

As a sign that insights are changing a more recent suggestion regarding the control of 3D gaze shifts proposed that saccades and fast vergence have a shared gating system for movement initiation (Mays and Gamlin 1995, 1996; Zee et al. 1992). Common gating would be reflected in a strong temporal (WHEN) coupling between the latencies of saccade and fast vergence responses. The finding that pure vergence movements can be slowed down by electrical (E)-stimulation in the OPN region suggests that pause neurons can indeed affect the vergence system, directly or indirectly (Mays and Gamlin 1996). These studies suggest that there is a greater degree of interaction between the two subsystems than was previously perceived.

Arguing further against thinking in terms of independent subsystems, it has been shown that binocular refixations, made up of combined version-vergence eye movements, are not simply linear summations of the required components executed in isolation (Collewijn et al. 1995, 1997; Enright 1984, 1986;

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Erkelens et al. 1989; Maxwell and King 1992; Oohira 1993). The vergence component, when combined with a saccade, is substantially faster than a normal pure vergence response, which implies that sensory feedback would be unlikely in this case. A recent study provided strong evidence for a shared saccade-vergence target selection system, where the metrics (WHERE) of the saccadic and vergence components of planned movements are jointly determined (Chaturvedi and Van Gisbergen 1998). In line with this idea, this study explores to what extent the SC, generally held to be a saccadic control center, may also be involved in the control of vergence movements.

Possible role of SC in neural control of vergence eye movements

For the sake of clarity, three different possible scenarios (see Fig. 1) regarding the involvement of the SC in vergence control will now be developed. One extreme point of view (the "non-involvement" hypothesis), shown in Fig. 1*A*, entertains the view that saccades and vergence are implemented by entirely separate control systems. This implies dedicated WHERE and WHEN mechanisms for each distinct oculomotor subsystem. Because the SC is obviously heavily involved in saccadic control, simple logic implies that this view precludes its involvement in vergence movements. Any artificial intervention in the colliculus would only affect the conjugate response and have no vergence effect whatsoever.

An alternative idea (the "indirect involvement" hypothesis), shown in Fig. 1*B*, is that saccades and vergence have a shared WHEN system (Mays and Gamlin 1995, 1996; Zee et al. 1992). As for the dedicated WHERE system, the scenario of indirect involvement entails that the SC specifies only the metric of saccadic eye movements, leaving vergence-dedicated WHERE control to some other neural center (Judge and Cumming 1986; Mays 1984; Mays et al. 1986). The postulated WHEN coupling in both systems may be implemented through gating by omnipause cells further downstream. Accordingly, the indirect involvement hypothesis implies that collicular microstimulation may indirectly have an effect on vergence initiation but not on its metrics.

A third possibility to be considered (the "direct involvement" hypothesis) is that the SC is involved in the WHEN and WHERE mechanisms of both saccade and vergence subsystems (see Fig. 1*C*). A number of electrophysiological studies (Bacon et al. 1998; Billitz and Mays 1997; Dias et al. 1991; Gnadt and Beyer 1998; Jiang et al. 1996; Mays 1996) proposed that the SC may indeed have some involvement with eye movements in depth. If this view is correct, stimulating in the SC in principle should affect not only the onset of saccade and vergence responses but also bias their metrics.

It occurred to us that a suitable and effective way of testing the 3D colliculus hypothesis would be to intervene artificially in the SC by E-stimulation. We carried out microstimulation perturbation experiments in the caudal SC with the intention of studying the initiation (WHEN) and metric-specification (WHERE) mechanisms of 3D eye movements. Before we explain the logic behind this approach, we briefly review earlier SC stimulation studies.

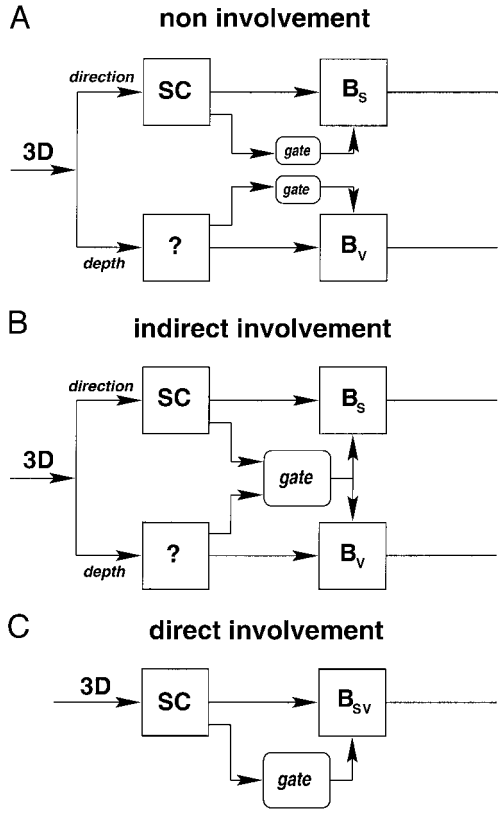

FIG. 1. Schematic of 3 models that depict different possible degrees of collicular involvement in saccade-vergence coordination. Each has a common 3-dimensional (3D) input, based on a higher-level common target-selection mechanism (see Chaturvedi and Van Gisbergen 1998). *A*: noninvolvement hypothesis exhibits the notion that saccade and vergence control is carried out by 2 distinct and separate oculomotor systems. A distinguishing characteristic of this model is the individual gating (WHEN) mechanism for both subsystems. The common 3D input is first separated into directional and depth components. The horizontal and vertical signals are fed to the 2-dimensional (2D) superior colliculus (SC) that controls the conjugate saccadic response. The SC sends a displacement signal to purely saccadic burst cells (B_s) downstream. When the bursters are enabled by the saccadic gate, embodied by the omnipause neurons (OPNs) in the brain stem, they send a velocity signal to the motoneurons. A very similar scenario is depicted for the vergence system. This presupposes pure vergence-command neurons in a separate unknown neural region (?), a dedicated timing mechanism, and pure vergence bursters (B_v). *B*: indirect involvement model differs only from the previous scheme in that it has a common gating mechanism. Thus the timing of both subsystems is identical, but each controls its own metrics. *C*: direct involvement model follows logically as another possibility from the previous 2. It assumes not only a common timing (WHEN) mechanism but also a common metric-specification (WHERE) system. Here the SC is assumed to code both directional and depth information for binocular responses in 3D visual space. OPNs control the gating of bursters (B_{sv}) that are involved in coding both the direction and depth coordinates of rapid eye movements in each eye separately (see Zhou and King 1998).

Earlier E-stimulation studies in SC

Neurons in the deeper layers of the caudal SC burst for saccadic eye movements in a limited range of directions and amplitude (Sparks and Mays 1980; Sparks et al. 1976; Wurtz and Goldberg 1972). High-frequency stimulation at caudal collicular sites elicits short-latency fixed-vector saccades (Schiller and Stryker 1972; Robinson 1972) by recruiting the brain stem burst neurons that are normally kept silent by omnipause cell inhibition (Raybourn and Keller 1977). Glimcher and Sparks (1993) have shown that low-frequency E-stim-

ulation in the caudal region of the monkey SC, before the initiation of a V-guided saccade, can influence the metrics (direction and amplitude) of the ensuing target-directed response. They suggest, in agreement with results from previous studies (Becker and Jurgens 1979; Glimcher and Sparks 1992; Sparks and Mays 1983), that signals specifying the metrics of saccades develop gradually after target presentation. Sparks and Mays (1983) used high-frequency stimulation in caudal collicular sites to elicit an E-induced saccade before an impending V-guided saccade and found that the metrics of the E-saccade could be altered by target location. The degree to which the saccade was dominated by the E- or the V-stimulus depended on the time interval between target onset and stimulation onset. They suggested that stimulation of the SC caused the V-induced motor error signal, which was being specified at the time, to be expressed.

Possible outcomes of combined EV-stimulation

To explore the three hypotheses outlined previously (see Fig. 1) we applied a similar paradigm in a 3D V-task to see if the V-specified vergence signal that is presumably building up would manifest itself in the E-triggered response in a similar way to the saccadic signal described previously. In our experiments we perturbed the system by applying E-stimulation at a time when the monkey was preparing or just initiated a 3D refixation to a newly presented target. Our goal was to see whether any effects on the vergence component along with the expected change in the saccade response could be demonstrated.

On the basis of results found previously in the frontal plane (Sparks and Mays 1983), the saccadic vector can be expected to exhibit a gradual change in its metrics from purely E- to more V-dominated when the E-stimulus is applied later and later in the trial. However, one would still expect an E-effect in late-stimulation trials where the monkey just initiated the V-guided response itself so that V-dominance will not reach the 100% level (Schlag-Rey et al. 1989). In other words, the expected effect of the perturbation on the saccadic system involves both a WHEN and WHERE aspect; saccadic responses can be triggered prematurely, and even when they are not (in the case of self-initiated movements) their metrical properties are affected by the E-stimulus. In the case of vergence, predictions are different for each model. First, if one takes the view that the SC is a saccade-related area (noninvolvement), one would not expect any vergence component as a result of premature stimulation. Alternatively, the indirect involvement hypothesis, which rests on the assumption of common gating, suggests the possibility that a premature E-triggered vergence response toward the V-stimulus may emerge. Finally, if the SC is involved in the control of the WHEN and WHERE systems of both saccades and vergence (hypothesis 3), one would expect not only a vergence response resulting from premature stimulation but also when E-stimulation is applied to ongoing self-initiated movements.

This study illustrates the actual effect of the combined E- and V-stimulation on the initiation and metric specification of binocular refixations. The results show that the WHEN and WHERE control, for both saccadic and vergence systems, is closely related and can be manipulated by artificial intervention in a stereotyped fashion.

METHODS

Animal preparation and neurophysiological procedures

SUBJECTS. The experiments were performed in two adult male rhesus monkeys (monkeys I and II), weighing 8–9 kg, that were trained to accurately fixate and follow V-targets presented in 3D V-space. The animals were water deprived and received a liquid reward after each correct trial. All surgical and experimental procedures were approved by the university committee for the use of experimental animals.

To prepare the animals for chronical neurophysiological experiments, three separate sterile surgical procedures were performed. We first fitted a solid cement cap to the skull to allow rigid fixation of the head of the monkey during experiments (for details, see Melis and Van Gisbergen 1996). Subsequently, after a method described by Judge et al. (1980), thin, gold-plated copper rings were implanted underneath the conjunctiva of each eye. These rings, which became firmly attached to the eyes by connective tissue, allowed us to record binocular eye movements. Finally, a stainless steel recording chamber was stereotaxically implanted over a trephine hole, centered on the midline, such that both colliculi could be reached by microelectrode penetrations.

RECORDING OF NEURONAL ACTIVITY. Extracellular activity in the SC was recorded with glass-coated tungsten microelectrodes (impedance 0.5–1.2 MΩ) inside a transdural guide tube. After amplification and filtering the electrode signal was fed into a level detector for spike detection.

The localization of the SC was based on a number of electrophysiological criteria, as described by Melis and Van Gisbergen (1996). Saccade-related burst neuron activity was encountered in the deeper layers of the SC. Here saccades could be reproducibly elicited by E-stimulation at low current strengths (10–50 μA). These saccades corresponded in size and direction to the contralateral movement fields of nearby saccade-related cells. The optimal saccade vector found in each penetration could always be accounted for on the basis of the topographically arranged map of the SC (Robinson 1972).

Both monkeys were stimulated in the right caudal SC, leading to saccades with leftward horizontal components. We reliably elicited different amplitude saccades at 22 different collicular sites ($n_{\mathrm{I}} = 7$; $n_{\mathrm{II}} = 15$). Histology, done in monkey I afterward, confirmed that penetrations were done in the deeper layers of the right SC.

Experimental procedures and setup

BINOCULAR EYE POSITION RECORDING AND CALIBRATION. Two-dimensional (2D) binocular eye positions were recorded with the double magnetic induction technique (Bour et al. 1984). Two alternating perpendicular magnetic fields (horizontal: 30 kHz; vertical: 50 kHz) induced eye position-dependent currents in the implanted eye rings, which in turn induced secondary currents in sensitive pickup coils that were mounted directly in front of each eye (interocular distance: 3.5 cm). A nulling coil, placed some distance away from each eye on a rigid manipulator, electronically canceled the primary (eye position independent) signal component induced by the magnetic fields. After amplification and demodulation by lock-in amplifiers (PAR 128A), the raw horizontal and vertical eye position signals were low-pass filtered (−3 dB at 200 Hz; 4th-order Bessel filter), sampled with 12-bit resolution at 500 Hz per channel, and stored for off-line analysis (details are described subsequently). The resolution of the recording technique was ~0.2° for eccentricities up to 25°. Careful inspection revealed that cross talk between the signals from the two eyes was negligible (<1° error for large horizontal angles) for our purposes. This was confirmed by other investigators who were using the same technique in cat studies (Malpeli 1998).

At the beginning and end of each experiment, the eye position signals of each eye were calibrated by requiring the monkey to binocularly fixate 85 targets throughout the oculomotor range, up to

eccentricities of 35°. Because the double-magnetic induction method is characterized by smooth direction-dependent nonlinearities (Bour et al. 1984), a neural network for each eye and each session was trained to map the raw eye position signals onto the known associated target locations (see Melis and Van Gisbergen 1996).

Saccades were detected as described by Melis and Van Gisbergen (1996). All trials were checked visually, and trials where the monkey blinked or did not fixate correctly were excluded.

STIMULUS PRESENTATION AND DATA ACQUISITION. Experiments were performed while the monkey sat, head fixed, in a primate chair. Light emitting diodes (LEDs; diameter 5 mm), positioned on a large circular board at a distance of 125 cm from the monkey, were used as V-targets to guide eye movements. The central LED was aligned with the cyclopean eye of the monkey. A number of LEDs were positioned on an adjustable perspex rod, roughly at eye level and closer to the monkey, thereby enabling the presentation of V-targets at various locations in the depth plane. Target presentation and stimulus timing were controlled by a PC. All experimental paradigms required the monkey to fixate a V-target before other targets were presented. For each trial, data recording always started 300 ms before the offset of this initial fixation point (FP) and continued for 2 s.

Perturbation paradigm

The objective of the perturbation paradigm was to elicit a saccade by E-microstimulation in the caudal region of the SC while the monkey was preparing a saccade to a V-target. The paradigm exploited the fact that, when a combination of E-stimulation and V-evoked activity occurs at different sites in the collicular map, the system may generate a saccade whose timing is related to E-stimulation onset, whereas its metrics may also reflect a V-guided influence, depending on relative timing of the E- and the V-stimulus. We tested whether 3D refixations were similarly affected, especially with regard to vergence metrics. To gauge the relative effects of the two stimuli in various temporal combinations, we recorded two control responses, i.e., an E-elicited eye movement (see Fig. 2*A*) and a purely V-evoked eye movement (see Fig. 2*B*). To determine the compromising character of the saccadic response in the forthcoming experimental paradigm we ensured that these controls clearly differed from each other in direction. The location of the FP was chosen freely in 3D space in these experiments, but once chosen it remained unchanged throughout the session.

To record the E-induced binocular eye movement (E-control), an E-stimulation pulse train was applied in the deep layers of the caudal SC while the monkey was fixating an LED. The FP was extinguished on stimulation, and after the E-saccade the monkey was rewarded. The pulse train (duration 50 ms; frequency 500 Hz) consisted of constant current biphasic pulses (BAK, Model BPG-1) with a duration of 0.2 ms. Initially, the threshold value for evoking saccades was determined by finding the current intensity where ≥90% of all stimulations led to a saccadic response. Experiments were then conducted with a suprathreshold current level of up to twice this value (between 20 and 70 μA) such that most saccades had a fixed amplitude. The E-control paradigm was repeated at the end of the experiment.

To obtain the purely V-guided control response, the monkey first had to fixate the FP. Directly after FP offset, a V-target was presented at one of a number of selected positions in 3D space, and the monkey made a V-guided binocular refixation (V-control) to the target. Care was taken to position the V-targets with respect to the fixation plane in either a far plane (requiring diverging eye movements) or a near plane (requiring convergence responses) such that there was a clear 3D directional difference between the E- and the V-response in both direction (Fig. 3*A*) and depth (Fig. 3*B*). An attempt was made to align both near and far targets such that refixations from the FP to these target LEDs required V-responses

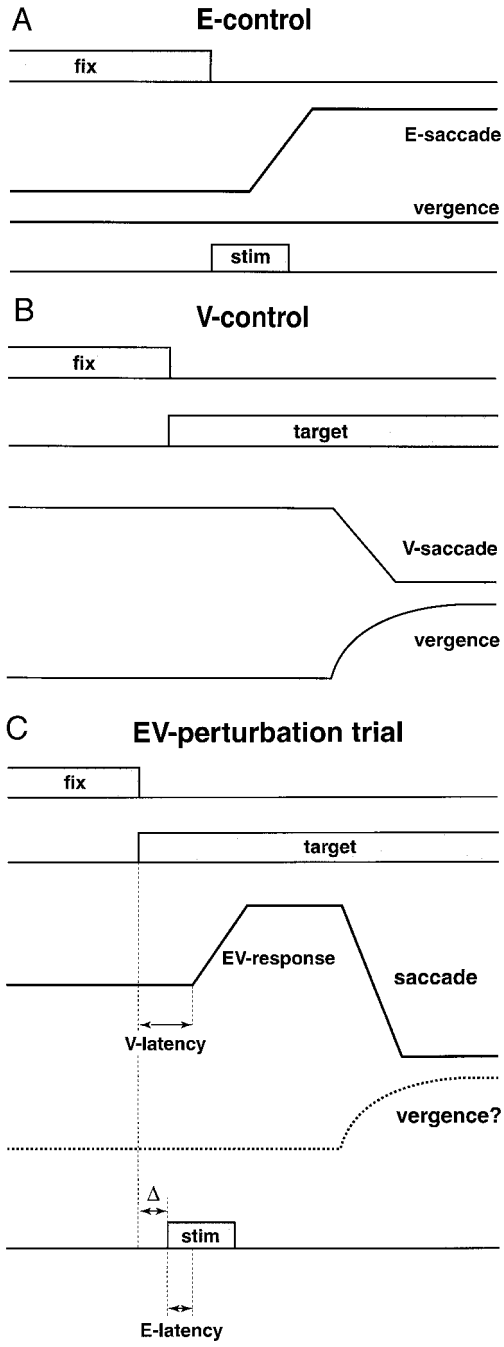

FIG. 2. Schematic representation of control responses in the perturbation paradigm. *A*: short-latency electrical (E) saccade is elicited (upward in this scheme) by stimulating suprathreshold in the SC when fixation spot is extinguished. This saccade vector corresponds with the chosen stimulation site in SC and appears to have no vergence component. *B*: V-evoked eye movement in 3D space to the light-emitting diode target presented downward from the fixation point (FP) and closer to the monkey. *C*: basic idea behind EV-trial in the perturbation paradigm where E-stimulation is applied at various E-delays (Δ) after the V-target was presented nearby. In this schematic example the stimulation pulse is applied fairly early, and after a short latency a saccade is elicited (EV-response). This is followed by a V-guided saccade that redirects the eyes to the V-target. Although it is not entirely clear what the disconjugate response will do, there was no a priori reason to expect that the initial EV-response would show vergence. The E-latency is the time delay between stimulation onset and the occurrence of the EV-saccade. V-latency of the saccade is the time between target onset and saccade onset.

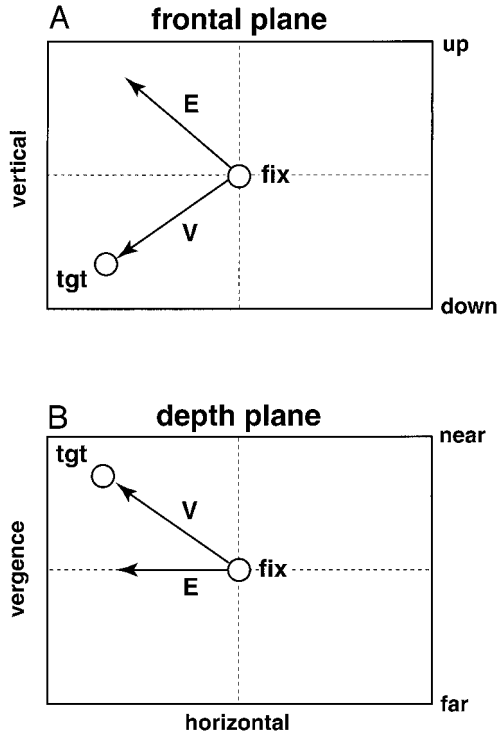

FIG. 3. The same schematic control responses from Fig. 2 projected on 2 different planes to show the spatial relations. Perturbation paradigm is set up such that there is a clear directional and depth difference in the E-elicited control and the V-evoked control. *A*: frontal plane view of FP (fix), target (tgt), E-control (E), and V-control (V). E-control saccade vector is directed obliquely upward. V-target was aligned in amplitude with the E-saccade and was directed to the lower hemifield. *B*: in a depth plane view of the controls we show that the E-control was not expected to have any vergence component, whereas V-response was directed nearby.

with saccades of roughly the same direction and amplitude. After choosing the target positions, a third set of experiments was started where fixation and depth-plane (both near and far) targets were randomly interleaved and where 30% of the trials required refixations with a vergence component.

To explore the effect of combined E- and V-stimulation (see Fig. 2*C*), in some of these 3D trials (20%), denoted as EV-trials, a stimulation pulse train was applied at various short delays (Δ) after the presentation of the V-target to induce a premature binocular eye movement. The onset time of the stimulation pulse train was varied from immediately after target onset to after V-saccade onset. E-triggered EV-responses were usually followed by a later V-guided response to the V-target, which corrected for the E-perturbation. E-stimulation generally only occurred when either the near or far target was presented. To minimize the possibility of predictive behavior during the V-guided refixations, a number of V-catch trials (where the FP was extinguished and no target was presented), stimulation catch trials (where no target was presented and stimulation was applied at FP offset), and eccentric targets, located along the four perpendicular axes in the far plane, were incorporated in each experimental session and presented at random times. The monkey was only rewarded at the end of the trial if correct fixation of the presented target was achieved. The monkey was rewarded in the catch trials and in the control E-trials if the fixation target was correctly attended to. Whenever the monkey did not fulfill a requirement set in our paradigm, the FP or target disappeared immediately and no reward was given. All experiments were done under dim lighting conditions.

RESULTS

E- and V-control responses

The perturbation experiments in this study were designed to investigate the involvement of the monkey SC in binocular refixations to targets in 3D V-space requiring combined saccade-vergence responses. The basic idea was to evaluate the effect of E-stimulation at one SC site on the 3D eye movement elicited by the V-target at another location in the SC map. As described previously (see Fig. 3) the E- and V-controls differed from each other in direction and depth, similar to the examples from a typical site shown in Fig. 4. The two panels on the left show both control responses projected together in the frontal and depth planes, respectively, whereas the three right-hand panels illustrate their corresponding time-courses. We aligned the LED target (tgt) in 3D space such that there was a clearly discernible difference in the vertical component of the two controls, keeping the magnitude of their horizontal components roughly similar. The V-response shown here, directed toward a near target, has a vergence component that can be separated into a fast intrasaccadic vergence phase and a subsequent slower movement. The eye movement generated on E-stimulation (E-response) is purely saccadic, and no evident vergence response is elicited. The slight divergence displacement during the E-saccade can be attributed to transient divergence (Collewijn et al. 1988, 1995; Maxwell and King 1992; Oohira 1993; Zee et al. 1992).

Qualitative observations

TEMPORAL ASPECTS. To introduce the analysis of the data, examples of EV-responses are depicted in Fig. 5, where the onset of the stimulation pulse train occurred at early, intermediate, and late stages after V-target presentation. The saccadic time courses are presented in Fig. 5 in the *top plots*, and the vergence components are presented in the *bottom panels*. By inspecting the time course of the vertical component of the combined EV-trials relative to the E- and V-responses (controls) we can evaluate how saccadic displacement changes as a consequence of E-stimulation. As will become clear, saccade behavior showed no surprises and conformed to the expectations formulated previously.

To illustrate this, Fig. 5, *left top panel*, shows that early E-stimulation, shortly after V-target onset, evoked a saccade that was very similar in magnitude to the E-response elicited in isolation. After a subsequent short delay the monkey made a V-directed saccade to fixate the V-target. Stimulation that occurred somewhat later in time, yet still before typical V-latencies, yielded a saccadic component (Fig. 5, *middle top panel*) that became larger in magnitude and further directed toward the V-target but was still temporally linked to the E-stimulation onset. Similarly, Fig. 5, *right top panel*, depicts an E-triggered saccade that was elicited late in the trial and was therefore more heavily influenced by the V-target. The metrics in this latter case are now a compromise between the E- and V-controls. Similar changes in saccade metrics were reported previously by Sparks and Mays (1983) in a frontal plane study where suprathreshold stimulation applied before V-guided saccades was seen to influence the metrics of V-guided saccades.

The corresponding eye movements in depth (Fig. 5, *bot-*

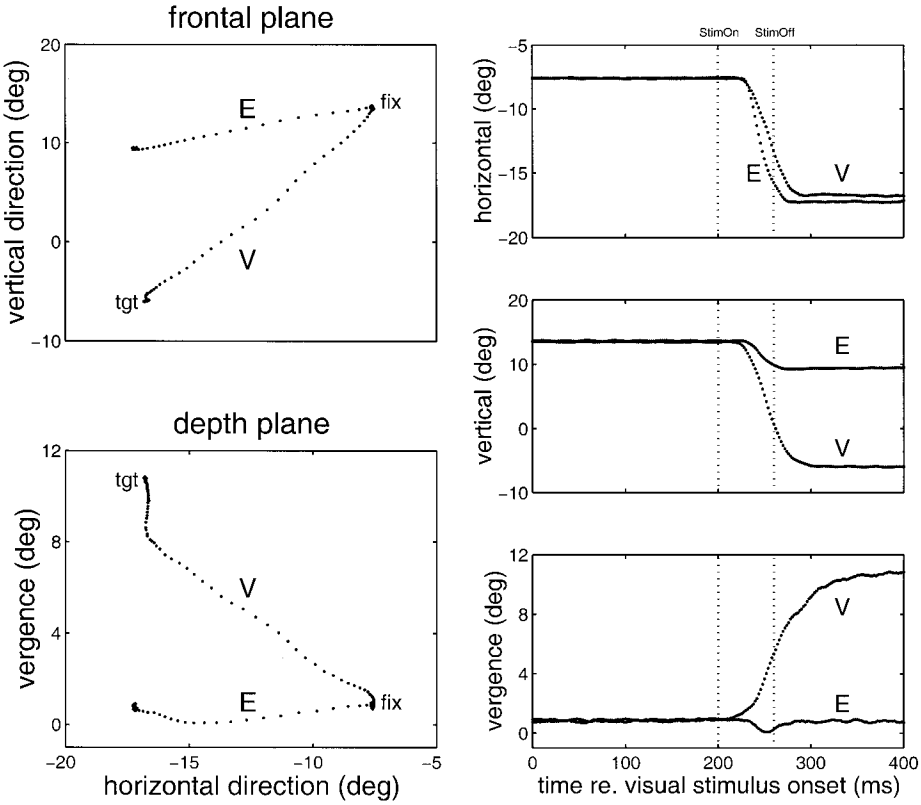

FIG. 4. Trajectories of actual control responses are presented in the format of Fig. 3 for both frontal and depth plane (horizontal plane of regard) views. The E-response exhibits no vergence component. The V-response is directed to a near target. Here, the FP (fix) is somewhat above eye level and slightly to the left of the cyclopean eye. Target location (tgt) was chosen such that, although vertical and vergence components differ considerably for both E- and V-controls, horizontal amplitudes are almost identical. In the time-course profiles the control responses are plotted with respect to V-latency. Data points occur every 2 ms. The E-response onset was temporally aligned with the V-response for sake of comparison. Onset and offset of the stimulation pulse train is indicated by the dotted lines. Data are from site I-3.

tom plots) show some interesting phenomena typical for all sites that appear to rule out the noninvolvement hypothesis right away. The *bottom left panel* shows that very early stimulation elicits no vergence. The vergence component of the EV-response closely resembles the control E-response, with only a small transient divergence component caused by the saccade. This is not the case in the *middle bottom panel*, which shows that intermediate stimulation elicits a small eye movement in depth, temporally aligned with the E-triggered saccade of the EV-response. Thus this fast vergence contribution is part of a combined premature saccade-vergence response that is E-initiated but target directed. This surprising phenomenon of a combined saccade-vergence movement triggered by collicular stimulation becomes even more unmistakable when stimulation occurs at a late stage (Fig. 5, *right bottom panel*) just before the expected V-response. Here both the E-triggered saccade and the associated fast vergence movement are larger in magnitude than the examples shown in the previous panels. Thus only when the E-stimulation onset occurs at a very early point in time does the target-directed vergence response fail to materialize. This manifestation of vergence, although clearly E-triggered, requires the presence of a 3D V-target because direct artificial intervention in the SC in isolation does not elicit any vergence whatsoever. The very occurrence of a vergence component in these E-triggered movements, inextricably linked to the E-evoked saccadic component, provides direct evidence against the noninvolvement hypothesis but is by itself insufficient to discriminate between the two remaining hypotheses.

METRICAL ASPECTS. To make this distinction we now reinspect the component displacements of the binocular refixations to compare them with the predictions put forward by each hypothesis. The notion of indirect involvement (see Fig. 1*B*) suggests that the E-stimulus causes a train of events that allows a V-induced vergence signal to be expressed prematurely but without adding any vergence WHERE contribution. Accordingly, if this view is correct, one should find averaging of E- and V-induced effects in the saccadic component but not in the vergence signal. As a corollary, V-induced movements that were E-perturbed in midflight in their saccadic component should not show any vergence effects.

The direct involvement viewpoint proposes that the E-stimulus not only triggers a premature movement but also produces saccadic and vergence WHERE signals. These E-induced WHERE signals then compete with the V-induced WHERE signals, yielding a compromise (averaging) response. That E-controls do not show any net vergence does not necessarily mean that they have no effect on vergence-metrics specification. A possibility that should be considered instead is that the absence of an overt vergence component in the E-control signifies a desired vergence change of zero amplitude rather than simply the absence of a vergence WHERE signal at the SC level (see DISCUSSION). If the E-stimulus would indeed induce such a zero-vergence change command, one can see how averaging may play an equally important role in the vergence response as in the saccadic response. As a consequence, collicular E-stimulation applied in midflight during a V-triggered 3D refixation should prevent the vergence response from reaching completion and becoming as "full-blown" as it might otherwise become. As will become clear from the following analysis, it appears that the experimental data are in accordance with the direct involvement hypothesis.

If the vergence traces in Fig. 5, *bottom panels*, are scruti-

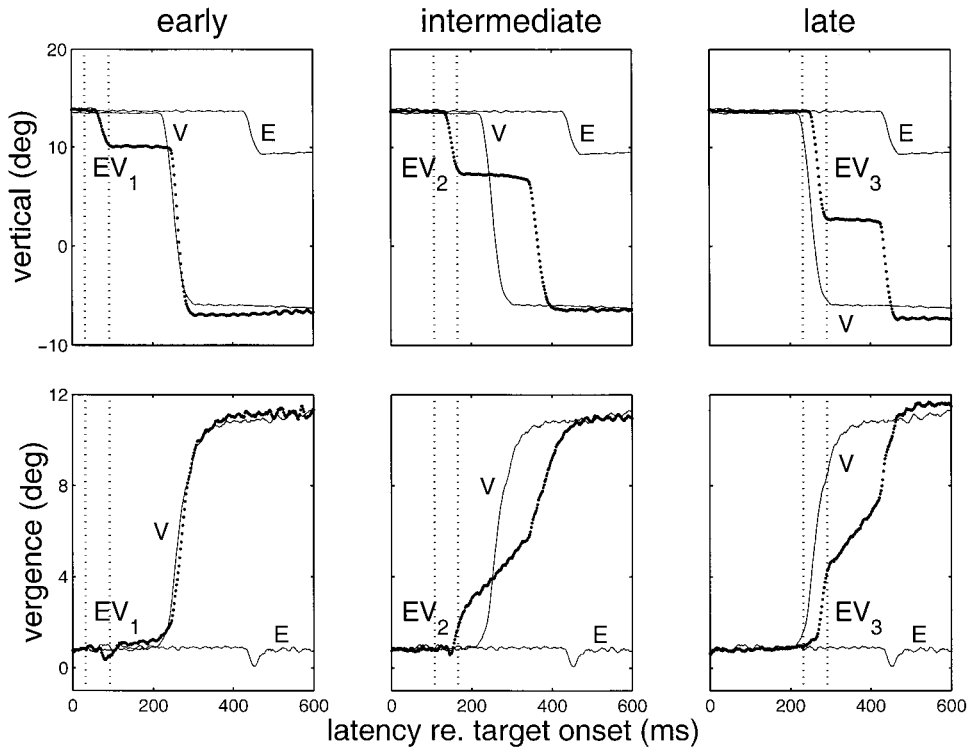

FIG. 5. Time courses of typical EV-responses, with E-stimulation (between dotted lines) applied at different points in time, alongside E- and V-controls (earlier shown in Fig. 4). Saccadic profiles are shown at the *top*, and the corresponding vergence components are shown in the *bottom panels*. In the first case (*left panel*), when stimulation is early, the E-response for both sets of components looks remarkably similar to the E-control. In other words, an E-saccade is elicited with no accompanying vergence response. The near target is subsequently fixated by an ensuing V-directed, combined version-vergence eye movement. In the next case (*middle panel*), when stimulation onset occurs a little later after target presentation, the E-triggered response is seen to be composed of a saccade and a small but unmistakable target-directed, fast vergence component. This is directly followed by a slow vergence eye movement in the direction of the target. After a short delay, a V-directed saccade and a corresponding fast vergence component occur to fixate the target. This same pattern is followed in the *right panel*. In this case, however, it appears that the later the stimulation occurs the larger the initial E-saccade and accompanying vergence components are. Whereas the saccadic time courses in the *top plots* can be clearly marked as having 2 distinct fast movements, the vergence profile in contrast has a more complex character. Data are from same site as in Fig. 4.

nized with these perspectives in mind, it becomes obvious that there is a gradual increase in the influence of the V-stimulus when the E-stimulus is given later and later in the trial. This trend toward V-dominance can be expected if indeed the vergence WHERE signal needs some time to build up. It is reasonable to assume that this WHERE signal will have reached an advanced state when the 3D refixation, whether E-triggered or initiated by the monkey, starts in the range of normal V-latencies. The crucial distinction between the two remaining hypotheses that we are now exploring is whether such late responses (see Fig. 5, *right panels*) show a full-blown fast vergence movement as in the V-controls. Actually it is clear that the E-triggered response is not close to being equal in magnitude to the V-controls. This is illustrated further in Fig. 6, where the trajectories of all three E-triggered EV-trials and controls (as seen in Fig. 5) are depicted in both the frontal and depth planes. As explained previously, this result may signify that a degree of averaging occurs between the E- and V-related signals and that the E-locus in the SC contributes an explicit zero-vergence change signal. In the further analysis, to be presented subsequently, we will investigate this suggestion in a quantitative manner with data from all sites. As a prelude to this quantitative treatment, it is important to ask what happens when the E-stimulus is given at a time when the monkey already initiated the eye movement.

MIDFLIGHT PERTURBATION EFFECTS. In Fig. 7 we present three examples of V-initiated responses where E-stimulation is applied in midflight after onset of the binocular refixation. It is a crucial finding that such a late E-stimulus perturbs not only the saccadic but, remarkably enough, also the vergence component. In each case the saccade time course closely follows the V-control until stimulation onset, after which the response deviates from its initial V-guided path toward the E-control. Interestingly, there is also a corresponding disturbance to the vergence response, temporally linked to the saccadic perturbation, where the V-guided vergence component breaks off its initial target-directed trajectory and diverges temporarily. As soon as the saccade picks up where it left off then so does the vergence. This is seen clearly in the spatial trajectories of the trials in Fig. 7, *A* and *C*, which are shown in Fig. 8.

In summary, it appears that presenting an E-stimulus at a very early stage of response preparation (i.e., just after target onset) elicits no net vergence and a saccadic component that is almost identical to the control E-response. If this perturbation

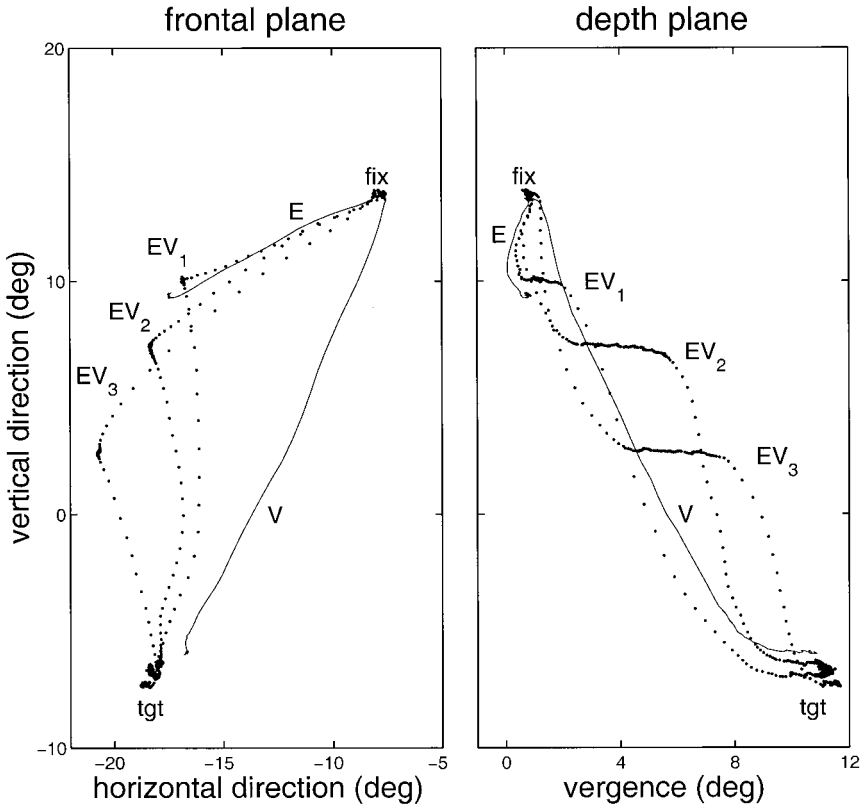

FIG. 6. Spatial trajectories of the trials and controls shown in Fig. 5 in frontal and depth planes. It is clear that the EV-responses show an averaging effect for both the vertical saccade and the vergence component, where the degree of compromise appears to be related to stimulation onset. Even for late stimulation, full-blown vergence is not seen. There is an unexplained increase in horizontal amplitude, despite the 2 controls being closely aligned.

is applied a little later, yet still before the monkey initiates a response to the V-stimulus, an E-triggered movement (EV-response) is evoked with a vergence component directed toward the V-target along with the expected saccade. The modulation of the metrics of each component appears to be related to the delay of the E-stimulation reflecting thereby a growing influence of the V-target on the entire 3D binocular refixation. A crucial observation arguing in favor of hypothesis 3 (collicular vergence WHERE signal) concerns the fact that, if a late E-stimulus is applied around the point in time where buildup of the V-target WHERE signal had time to reach a state of near completion, one does not see a complete vergence response resembling the V-control. The following sections will now analyze these data at a quantitative level.

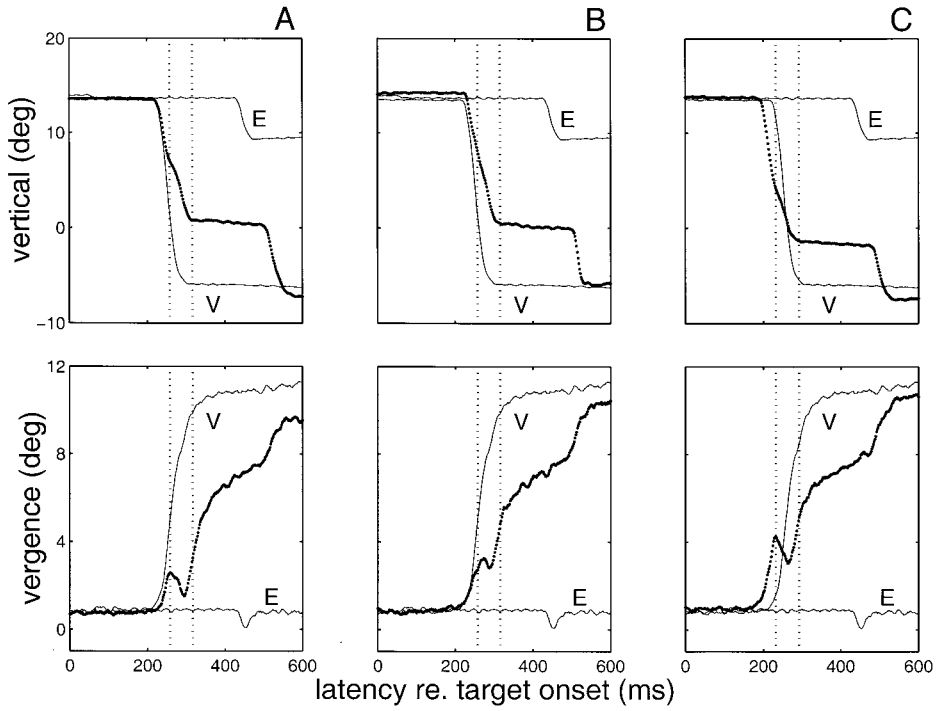

FIG. 7. Time courses of 3 EV-responses (*A–C*) where stimulation (between dotted lines) was applied during midflight, displayed in a format similar to Fig. 5. E-stimulation briefly perturbs the target-directed response toward the E-control for both the saccade and vergence response, although the eye movement was already initiated voluntarily. Whereas the saccade stops briefly after E-modification, the vergence continues toward the target, albeit slowly. Data are from site I-3.

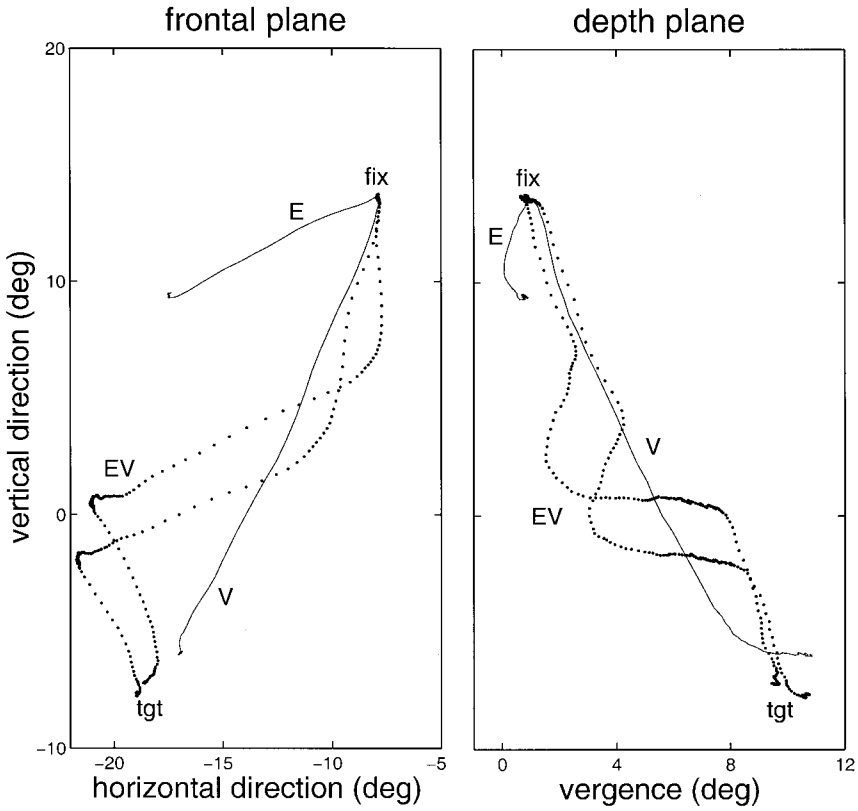

FIG. 8. Trajectories in both planes of trials *A* and *C* from Fig. 7 are shown together with control responses. The deviation and averaging effects for saccade and vergence components are very clear.

Quantitative analysis of metrical perturbation effect

In this analysis, it is important to keep track of how the binocular refixations in the E-triggered EV-trials, the V-stimulus and the E-stimulus, are temporally related to one another. Because E-stimulation was applied at a number of discrete delays relative to the V-stimulus, we obtained E-triggered responses over an extensive time period of target signal buildup, ranging from zero (E-stimulation at V-target onset) to nearly complete (V-latency range). When the E-stimulation was applied at a late point in time, the V-guided response could begin before stimulation onset so that in these cases E-latency (saccade onset with respect to E-stimulation onset) was negative. When E-stimulation occurred at a relatively early stage, all EV-responses were E-initiated, having rather constant E-latency values of ~20–30 ms. As one would predict, when E-delays (time between V-stimulus onset and E-stimulation onset, see Fig. 2*C*) were made long enough to enter the domain of V-latencies, the probability of getting a V-triggered EV-response increased sharply. To understand the additive effects of E- and V-stimulation, it is useful to consider how the characteristics of EV-responses develop both as a function of their timing relative to the V-stimulus (V-latency) but also as a function of E-latency. We will now proceed to present data, considered from either perspective.

METRICAL DEPENDENCE ON V-LATENCY. We present the entire range of EV-responses in Fig. 9, where the component displacements are now plotted as a function of V-saccade latency. Saccade amplitudes are depicted in Fig. 9*A*, and intrasaccadic vergence is shown in Fig. 9*B*. The mean control values for E-stimulation and V-guided refixations are also shown. If we first inspect the saccadic component in Fig. 9*A* we can see that E-triggered EV-responses (●) only attain roughly up to halfway completion. These EV-responses are fully E-dominated when their V-latencies are short (e.g., ~100 ms). The V-influence increases when the E-stimulus is delayed such that V-latency is prolonged. However, for long V-latencies we do not see complete V-dominance, at best a compromise between the two influences. This averaging effect continues to be present in the V-triggered EV-responses (○), which show a large degree of scatter in saccadic displacement. Similar conclusions can be drawn for the intrasaccadic vergence as a function of V-latency, shown in Fig. 9*B*. Here a compromising phenomenon is also seen for both E- and V-triggered EV-responses, and it is apparent that metrically the latter set of data points can range almost anywhere between E- and V-domination. E- and V-triggered EV-responses show a marked degree of overlap. A much clearer picture emerges if one analyzes how the interplay of competing E-stimulus and V-stimulus effects depends on the time shift between the E-stimulus and response onset (E-latency).

METRICAL DEPENDENCE ON E-LATENCY. This point is illustrated in Fig. 10 where each rapid component of the binocular refixation is plotted as a function of E-latency, linking the displacement in each component with its latency relative to the E-stimulus onset. A great deal of information is contained in this plot, and we start by considering the saccadic behavior, shown in Fig. 10*A*. Notice that EV-responses with the longest positive E-latencies, obtained by very early E-stimulation, are indistinguishable from the E-controls (top dotted line). The other extreme, responses that are fully V-dominated (indistinguishable from V-controls, indicated by the bottom dotted line), are those V-triggered movements where the E-stimulus came too late to affect the movement at all, that is, after saccade offset.

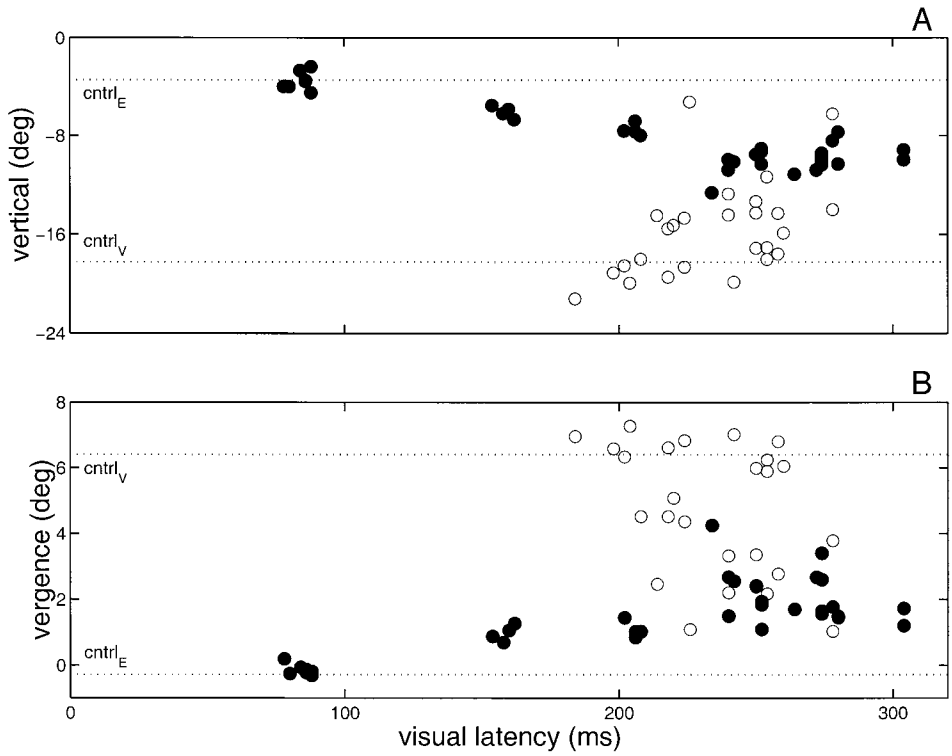

FIG. 9. Component displacements of EV-responses are presented as a function of V-latency (taken as primary saccade onset with respect to target onset). The dotted lines are the mean of all V ($cntrl_V$)- and E ($cntrl_E$)-control responses. *A*: responses show a slight trend from heavy E-influence to increasing V-influence in (vertical) saccadic displacement as latency increases. In the realm of actual V-latencies (>200 ms) both E- and V-triggered responses scatter between halfway completion and complete V-influence. *B*: similar trend is shown for vergence displacement. The E-influence is large for early V-latencies, and the V-influence increases for the V-latency range.

In between these two extremes there is a gradual transition of data points, which are observed to be at an intermediate stage of displacement when E-latency is zero. Because it seems reasonable to assume that the V-buildup signals reached the V-control level in all V-triggered EV-responses (i.e., negative E-latencies), the fact that the intercept value does not equal the V-control level indicates that the E-stimulus must be exerting a metrical effect on ongoing V-initiated movements. As previously noted, this is the critical distinction between hypotheses 2 and 3. Figure 10 shows that the E-triggered saccades become more and more V-affected as the E-latency diminishes toward zero. This clear change from E- to V-dominance continues further as E-latencies become increasingly negative. The picture that emerges therefore is one of an averaging process

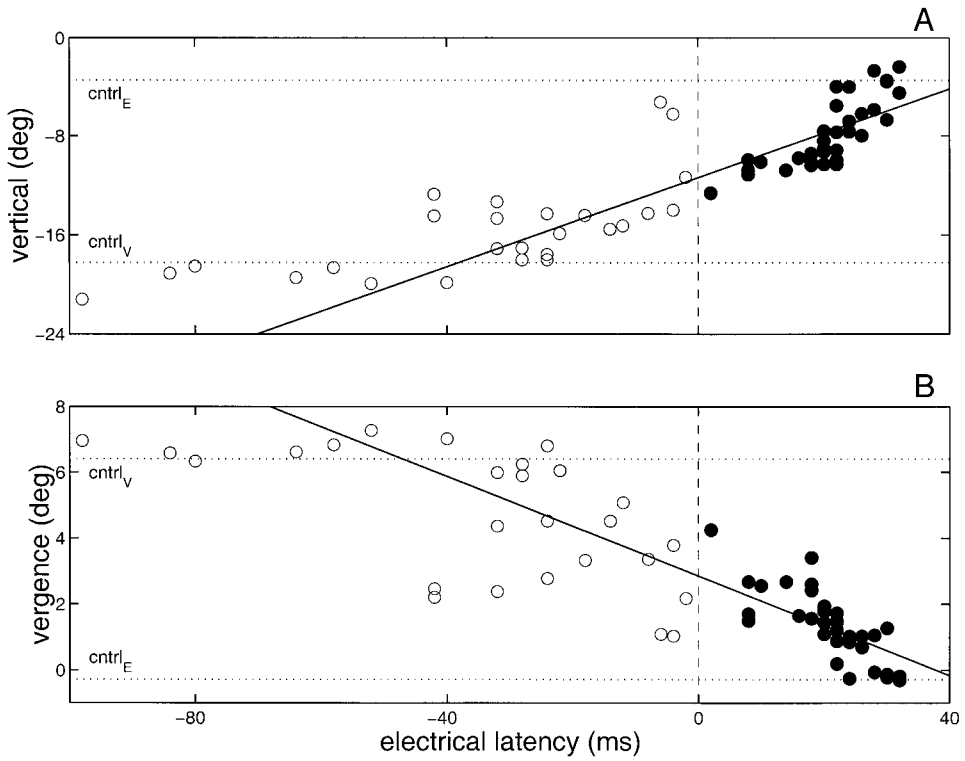

FIG. 10. Component displacements of EV-responses are presented as a function of E-latency (defined to be time between saccade onset and stimulation onset). The linear regression line fits the data points in the time window of ±40 ms. *A*: clear change in saccadic displacement occurs as positive latencies become smaller, i.e., as stimulation onset is delayed and E-latency decreases. Responses with negative latencies (V-triggered responses) are still heavily influenced when the E-stimulus occurs in midflight. A full saccade only occurs after ~40 ms when stimulation comes after saccade offset. *B*: similar trend is seen for the vergence component. Early stimulation (large positive latencies) does not lead to any vergence. When E-latency is 0, only halfway completion is attained. V-triggered responses (○) still do not exhibit full-blown vergence responses. This is also only seen after ~40 ms.

TABLE 1. *Perturbation indices*

Site	*n*	*i*, μA	E-sacc *R*, °	E-sacc Φ, °	Perturbation Index Saccade	Perturbation Index Vergence
I-1	42	70	2.5	170	0.62 ± 0.06	0.56 ± 0.08
I-2	19	35	5	180	0.36 ± 0.22	0.21 ± 0.22
I-3	51	30	15	190	0.46 ± 0.04	0.53 ± 0.20
I-4	47	25	7.5	180	0.69 ± 0.02	0.61 ± 0.14
I-5	50	70	10	200	0.61 ± 0.06	0.81 ± 0.06
I-6	38	70	5	120	0.75 ± 0.06	0.80 ± 0.06
I-7	33	30	15	180	0.57 ± 0.26	0.56 ± 0.28
II-1	29	40	20	155	0.41 ± 0.08	0.34 ± 0.10
II-2	33	30	17.5	170	0.31 ± 0.10	0.43 ± 0.12
II-3	36	25	20	135	0.46 ± 0.12	0.54 ± 0.22
II-4	48	30	25	100	0.31 ± 0.12	0.25 ± 0.10
II-5	44	20	27.5	165	0.46 ± 0.06	0.37 ± 0.08
II-6	46	20	12.5	160	0.52 ± 0.08	0.42 ± 0.08
II-7	66	40	15	120	0.40 ± 0.08	0.36 ± 0.10
II-8	91	40	25	150	0.42 ± 0.06	0.35 ± 0.06
II-9	23	50	10	135	0.24 ± 0.12	0.16 ± 0.12
II-10	25	25	22.5	145	0.35 ± 0.08	0.58 ± 0.14
II-11	35	35	15	120	0.28 ± 0.10	0.20 ± 0.16
II-12	17	30	5	120	0.35 ± 0.42	0.28 ± 0.50
II-13	29	20	7.5	100	0.15 ± 0.28	0.14 ± 0.22
II-14	43	30	7.5	135	0.32 ± 0.10	0.29 ± 0.12
II-15	116	40	10	110	0.38 ± 0.06	0.33 ± 0.10

An overview of all the stimulation sites from monkey I and II is given with the number of trials (*n*) used and the current intensity applied (*i*). The electrical (E) saccade vector, elicited by E-stimulation, is shown for each site (*R*: amplitude; Φ: direction). The normalized perturbation values (taken from the intersection with the zero electrical latency axis; see Fig. 10) are given for both sets of components with corresponding 95% confidence limits. Data from site I-3 are presented in Figs. 4–10, 12, and 13 for illustrative purposes. For site I-5 we used a time window of ±100 ms, and for site I-6 we used a time window of ±60 ms instead of the usual ±40 ms used in the linear regression for all other sites. For site II-12 data on V-triggered EV responses were not available.

that blends the evoked E- and V-signals, causing a gradual trend of data points that link the E-control response to the V-control response.

Interestingly, a remarkably similar situation can be seen for the intrasaccadic vergence (in Fig. 10*B*) as a function of E-latency. Again we see a progression from an E-type response to a V-type response going from right to left, similarly intersecting the zero-latency line at an intermediate displacement between the two control values. Here, too, the intrasaccadic vergence component of V-triggered EV-responses is smaller than in the V-controls, if the E-stimulus is applied in midflight. Clearly, if E-stimulation follows shortly after a self-initiated movement, the vergence response is also affected. This remarkable result, that the vergence data appear to follow the same trend as the saccadic components by showing the effect of an averaging process, is compatible with hypothesis 3 and argues against hypothesis 2. In terms of the latter idea, the gradual increase in vergence amplitude for E-triggered EV-responses would be interpreted as a gradually emerging vergence component of extracollicular origin that manifests itself through a common gating system, shared with the saccadic system. Thus the vergence signal would build up elsewhere and then be released by the combined saccade-vergence trigger, but there would be no contribution from electrical SC stimulation. However, according to this view, the vergence response should not be affected at all by too late SC stimulation (V-triggered EV-response) as far as its metrical properties are concerned. Thus in this scenario one would expect full-blown vergence responses, appropriate for the V-stimulus, when the E-stimulus comes so late that the movement was already triggered visually (i.e., negative E-latencies). This does not appear to be the case. The intercept of the linear fit, with the zero axis of E-latency, is notably lower than the V-control level. This and the ensuing V-initiated EV-responses show that at least in this site collicular stimulation caused a metrical effect on vergence, incompatible with hypothesis 2. In other words we see a compromise between the E-effect, tending to keep the vergence change at zero, with the steadily growing influence of the V-effect that increasingly attracts the eyes to the depth plane of the target. On the basis of these results we suggest therefore that the absence of a vergence component in the E-control (see Fig. 4) does not signify the mere absence of a metrical vergence signal but instead that the E-stimulus generates an explicit zero-vergence displacement command. Note for both components that, if the E-perturbation starts too late, ~40–50 ms after the monkey initated refixation, modification of the movement no longer occurs because the V-response was already completed. In this case all the data points can be seen to lie on or close to the V-control line.

QUANTITATIVE EVALUATION OF HYPOTHESES. To gain a quantitative measure for each site that characterizes the important relationship between the metrics of the responses and the E-latencies, we applied a linear regression analysis to the data points within a selected temporal window. By choosing only the responses that make the transition from the E- to the V-control lines (roughly between ±40 and −40ms) we were able to gauge the intercept of the EV-responses on the dashed line in Fig. 10 representing zero E-latency. For the site shown in Fig. 10*A*, the intersection point is roughly midway between the E-control and V-control lines. This provides strong evidence that the two regions of activity (E- and V-activated) still compete strongly with each other after the V-guided refixation was initiated. To ascertain to what extent the picture emerging

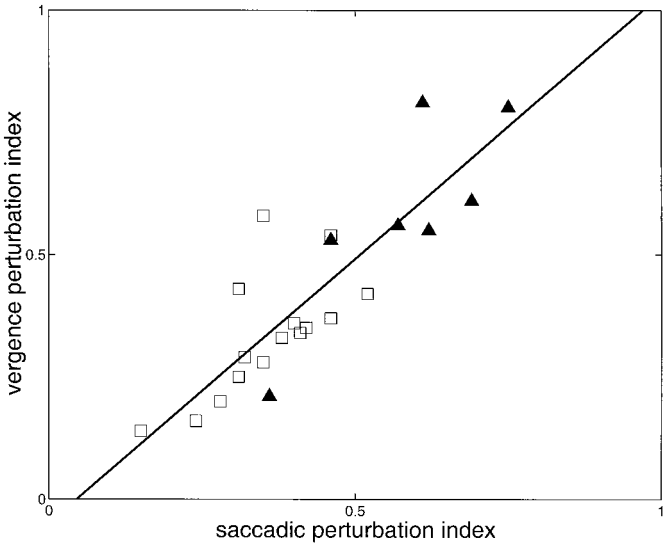

FIG. 11. Perturbation values for both sets of components, for all sites in both monkeys, are plotted against each other. The linear regression line is shown and has a correlation coefficient of $r = 0.86$ ($n = 22$). Sites from monkey 1 (▲) are perturbed somewhat more, in general, than sites from monkey II (□). Both sets lie fairly close to the regression line.

from Fig. 10, favoring hypothesis 3, is representative we provide a quantitative overview of all sites (see Table 1).

The intercept values are crucial in testing the prediction of hypothesis 3, that both the saccade and the vergence components of V-initiated EV-responses show perturbation effects. Accordingly, all the intercepts must lie between the E- and V-controls. To allow easy comparison of data from different sites, we normalized the intercepts on a scale from zero to one, with the E-control (unity) and the V-control (0) as reference values. This measure, which becomes larger the closer the intercept approximates the E-control level, is a direct measure of the perturbation effect of the E-stimulus and will therefore be denoted as the perturbation index (P). To illustrate, the P values for the saccade and vergence components from the site shown in Fig. 10 were determined as 0.46 and 0.53, respectively, indicating that perturbation was substantial. We present the perturbation indices for both sets of components in Table 1 for all the sites. Note that, although there is a large degree of variation in perturbation indices for vergence, all sites show a vergence WHERE effect caused by E-stimulation ($P > 0$). The accompanying 95% confidence limits for each site are an indication of the statistical uncertainty in P and show that there is a significant perturbation effect for virtually all sites (20/22 for saccades; 17/22 for vergence). Sites showing only a weak perturbation index for vergence also tend to have a correspondingly low P value for saccades, indicating that the E-stimulus was relatively ineffective in these cases. We now explore to what extent the variability among sites (see Table 1) and the variability from trial-to-trial (scatter in data points) in the behavior of the saccadic system are correlated to the variability in the vergence system. These factors, which are of importance in evaluating hypothesis 3 in further detail, will be analyzed in the next section.

Similarities in saccade and vergence perturbation effects

CORRELATED PERTURBATION EFFECTS. If the basic idea behind direct involvement is correct, the possibility has to be considered that the proposed involvement of the SC in both saccades and vergence may cause functional linkages between the WHERE signals of the two oculomotor subsystems by the introduction

TABLE 2. *Goodness-of-fit values (r^2)*

	Latency Dependence		Metrical Relationship		
Site	Saccade	Vergence	No Correction	Latency Correction	Duration Correction
I-1	0.91	0.87	0.89	0.25	0.83
I-2	0.79	0.85	0.95	0.77	0.88
I-3	0.73	0.69	0.86	0.59	0.83
I-4	0.92	0.73	0.86	0.55	0.77
I-5	0.89	0.69	0.66	0.03	0.67
I-6	0.80	0.77	0.96	0.83	0.92
I-7	0.51	0.41	0.81	0.67	0.76
II-1	0.87	0.79	0.76	0.07	0.79
II-2	0.80	0.66	0.87	0.62	0.83
II-3	0.74	0.40	0.77	0.76	0.83
II-4	0.78	0.85	0.90	0.53	0.94
II-5	0.92	0.69	0.70	0.07	0.74
II-6	0.92	0.92	0.94	0.41	0.96
II-7	0.91	0.81	0.88	0.34	0.90
II-8	0.91	0.89	0.86	0.08	0.90
II-9	0.86	0.86	0.71	0.02	0.88
II-10	0.77	0.46	0.64	0.35	0.66
II-11	0.90	0.82	0.90	0.45	0.93
II-12	0.81	0.70	0.91	0.69	0.90
II-13	0.66	0.79	0.85	0.52	0.86
II-14	0.91	0.88	0.93	0.46	0.88
II-15	0.90	0.76	0.88	0.50	0.76

An overview of the r^2 values characterizing various temporal and metrical relationships for all sites. The latency dependence data present the goodness-of-fit values (r^2) for the linear regression applied to a plot of EV-response displacement as a function of electrical latency (see Fig. 10). This is shown for both components. The metrical correlation presents the goodness of fit for the linear regression applied in the data plot between intrasaccadic vergence and saccadic displacement (see Fig. 12). The table also documents the remaining strength of this metrical relationship after we have corrected for the effects of E-latency and saccadic duration, respectively (2 right-hand columns).

of a common noise source. To assess whether such couplings can in fact be demonstrated, we further examined the perturbation data from Table 1. What causes the variability in *P* values is not known (see DISCUSSION for a suggestion), but it is clear that if the scatter in saccadic *P* values strongly correlates to the variation in vergence *P* values, this would support the idea that these causes work equally on both subsystems. We compare *P* indices for saccades and vergence for all the sites, from both monkeys, in Fig. 11. The best-fit line has nearly a unity slope and a correlation coefficient that is highly significant ($P < 0.01$), showing that the perturbation effects in the saccade and vergence components of the binocular response covary and, interestingly, that they are about equally strong.

ANALYSIS OF TRIAL-TO-TRIAL VARIABILITY. The plots in Fig. 10 show that there is a linear relationship between the degree of perturbation and E-latency both for saccades and vergence. This strong relation with E-latency was observed for almost all sites, as shown by the data presented in Table 2 for both saccadic and vergence components. There also appears to be a considerable degree of scatter in displacement for the V-triggered responses that are perturbed in midflight. Given that a trial-to-trial variation exists in the relative effects of the V- and E-activity, one wonders whether this scatter in the saccadic and the vergence component is also correlated. In other words, if the V-effect in a particular trial is especially small or large in the saccadic component, relative to the fit curve, would the corresponding vergence component then show concordant variations? To explore the possibility that a common noise source is affecting the metrical effects in both components on a trial-by-trial basis we plotted the various component displacements against each other in Fig. 12. Of course, if the trial-by-trial scatter were independent in both subsystems, one would still expect the two components to be correlated in this plot because of their shared dependency on E-latency (shown in Fig. 10). The impression at first glance is that the very strong relationship between the conjugate and disconjugate responses

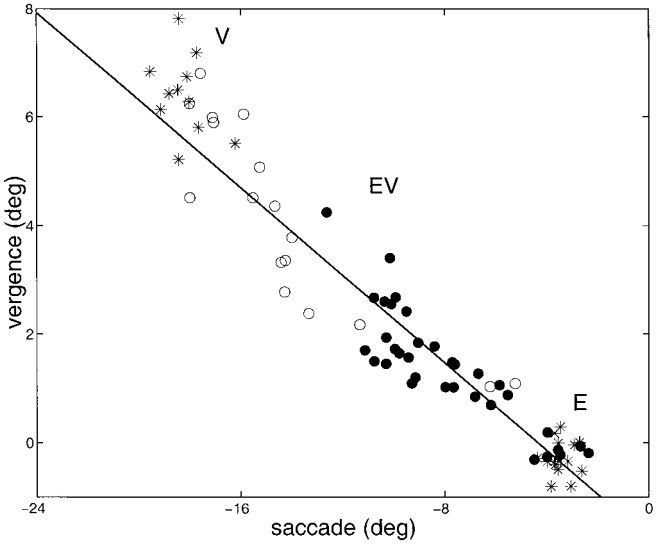

FIG. 12. Component displacements plotted against each other for the site shown in Fig. 10. The EV-data points, spanning the range between the 2 sets of controls (*), marked by E and V, exhibit a strong correlation ($R^2 = 0.86$; $n = 51$). As saccadic displacement increases, intrasaccadic vergence increases accordingly. This is true not only for the E-triggered (●) responses but also for the V-triggered responses (○).

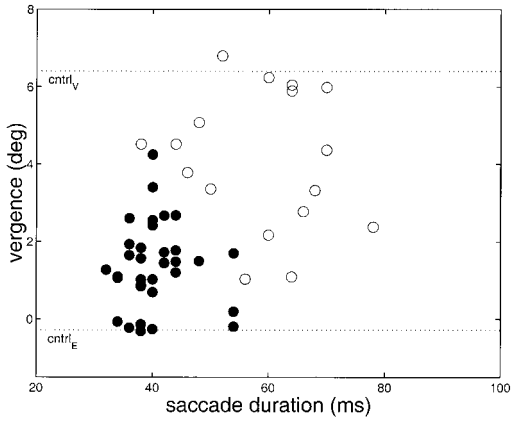

FIG. 13. Intrasaccadic vergence displacement presented as a function of saccade duration for the entire set of EV data points shown in Fig. 12. The low correlation indicates a weak relationship that does not account for the strong correlation seen in Fig. 12.

of each binocular refixation is unlikely to be merely an epiphenomenon of the shared latency dependence. As Table 2 shows, a high degree of metrical correlation between saccades and vergence was seen for all sites. In more than two-thirds of the sites, 85% or more of the variability in vergence can be accounted for on this basis. To determine the contribution of trial-to-trial variability, it is necessary to filter out the latency contribution with partial correlation analysis. After this was done (see Table 2), we see that a substantial correlation remains in the majority of sites. This means that the trial-to-trial variability, causing scatter about the metric–latency relationship (see Fig. 10), is not independent for the saccadic and vergence components. To illustrate, in one-half of the sites ≥50% of this variability can be ascribed to this common noise factor (see Table 2).

Vergence changes are not on epiphenomenon of varying saccade duration

In our analysis, we concentrated on intrasaccadic vergence as a clearly defined signal for comparison with the saccade behavior. However, this means that the following caveat has to be considered. One might argue that modification of the saccade metrics by the E-stimulus might, by virtue of the amplitude–duration relationship of saccades, influence the time-window in which rapid vergence can express itself. Although our experimental setup was expressly designed to sidestep this potential problem, by attempting to keep the amplitude of the saccade vector nearly constant (see METHODS), it was inevitable that saccades would vary in amplitude and therefore also in duration. The question to be answered now is to what extent these unintended duration effects may have determined intrasaccadic vergence displacement indirectly. To illustrate the problem, we examined this issue for the responses shown in Fig. 12. The data points depicted in Fig. 13 show the intrasaccadic vergence as a function of saccade duration. It appears that there is only a weak relationship between the two parameters, which in this site would only account for some 22% in the variance of the vergence component ($r^2 = 0.22$). To gauge how significant a role saccade duration plays in causing the metrical correlation with the vergence signal, we performed a partial correlation analysis for all sites by controlling for the

influence of saccade duration. If the strong correlation in Fig. 12 were an epiphenomenon of variations in saccade duration, it would be lost after performing this further statistical analysis. What becomes clear from Table 2 is that the strong correlation between the saccade and vergence displacements, as seen for all sites, cannot be unduly considered to be an epiphenomenon of varying saccade duration. The r^2 values in the column on the righthand side of Table 2 reflect the genuine relation between the metrics of saccades and vergence after controlling for saccade duration effects. The relationship between the saccade and vergence metrics clearly remains very strong.

DISCUSSION

We undertook neurophysiological experiments in the SC to learn more about the neural substrate of combined saccade-vergence eye movements. The oculomotor system was perturbed by E-stimulation in the SC at a time when the monkey was preparing, or just initiated, a 3D refixation to a newly presented target. Our goal was to see whether any effects on vergence, besides the expected changes in saccade responses, could be demonstrated. Results from our perturbation paradigm have shown not only the occurrence of premature E-triggered (and V-directed) vergence responses but also the weighted averaging of the two sets of stimuli (E and V) as a function of stimulation onset for both sets of components. Furthermore, data from V-triggered EV-responses show that the vergence response reveals a highly similar degree of perturbation as the corresponding saccadic portion.

Absence of vergence in E-induced refixations

To differentiate between the E- and V-triggered portions of EV-responses in the perturbation paradigm, the experiment was designed such that separate E- and V-stimulation yielded control responses with clearly distinct saccade and vergence directions (see Fig. 4). The results indicate that the greatest part of the required convergence, in the V-controls, takes place during the fast intrasaccadic phase. The E-control trials consistently yielded the saccade expected on the basis of the stimulated site in the SC motor map but did not exhibit any vergence response. This data are in line with findings recently presented by Billitz and Mays (1997), who observed that stimulation of caudal and rostral sites, while a monkey fixated a distant target, did not lead to any vergence effects. If interpreted in a straightforward manner as a sign that the SC is only involved with saccade control, this fact would lead one to believe that E-stimulation, applied in conjunction with a V-target in 3D EV-trials, will only interfere with the required saccadic response, leaving vergence unaffected. It is evident from our results (see Figs. 10 and 11 and Table 1) that this explanation has become untenable.

Rejection of noninvolvement hypothesis

Yarbus' (1967) suggestion that refixations in 3D space are a result of distinct and independent oculomotor subsystems and neurophysiological work indicating that saccades and vergence responses may be coded in different areas of the brain (Judge and Cumming 1986; Mays 1984; Mays et al. 1986) provides a basis for the noninvolvement hypothesis, outlined in the INTRODUCTION. If, as in this proposal, each subsystem is considered to be an independent entity, then no room is left for a common WHEN and/or WHERE control mechanism for the two components. On the basis of the results from previous studies (Glimcher and Sparks 1993; Sparks and Mays 1983) one would expect, in the perturbation paradigm, that the saccadic response shows a gradual change in displacement between the two sets of controls as the onset time of the E-stimulus is delayed. A specific prediction from the noninvolvement model is a zero-vergence response (as seen in the E-control) for all positive E-latencies (i.e., cases where the E-stimulus is applied before any V-triggered response occurs). In addition, a full convergence response, unmitigated by the E-stimulus, should occur when a V-guided response is initiated toward the near target, in other words, when E-latencies are negative.

Because both vergence predictions are in conflict with the data, the model must be discarded. Next we will evaluate the second model that can account for the subset of our experimental results showing that (V-directed) vergence is elicited prematurely as a result of the E-stimulation in the SC. This novel result (see Fig. 5) shows that, by intervening in the SC during the time period of V-signal buildup, one can affect not only the saccadic response but also the vergence response.

Evaluation of indirect-involvement model

PREMATURE E-TRIGGERED VERGENCE RESPONSES. E-stimulation, in the indirect involvement model, opens the gate for both sets of components (in whichever state of preparation they may be). If we assume that the vergence signal is built up gradually, this model can explain why the V-directed vergence signal is able to manifest itself prematurely after application of the E-stimulus in the SC.

Our results show how varying the delay of the E-stimulus can reveal the magnitude of the gradually increasing V-contribution to the saccadic component. What we see in Fig. 10*A* is that when stimulation is applied shortly after V-target presentation the saccade elicited is strongly reminiscent of that seen during the E-control. When stimulation occurs later but nevertheless before a V-guided response, the E-triggered saccade is being increasingly influenced by the V-signal. Because, apparently, V-signal buildup occurs gradually over time, the V-influence becomes stronger as the onset of the E-stimulus is delayed. These observations are very similar to what was described earlier by Sparks and Mays (1983) for suprathreshold high-frequency stimulation in the SC. Although the purpose of their study was different, they also observed that the vector of an E-triggered saccade was influenced by a V-target that had been presented earlier. The degree of modification depended on how long the V-target was present before stimulation onset.

What vergence-related outcome might be predicted on the basis of the indirect involvement model? If an E-stimulus applied to the SC initiates a movement and if as proposed the distinct neural regions for saccade and vergence control are connected with a common initiation mechanism, then the vergence signal being built up will be released. This so-called premature vergence signal is what we see from our experiments. The E-stimulus has an almost identical effect on the vergence signal as on the saccade signal (see Fig. 10). This would mean, in the context of the indirect involvement model, that the buildup of the distinct V-signals after V-target presen-

tation in the two separate neural regions occurs in a similar fashion. In other words, we see an increasingly larger 3D target-directed response occurring later and later in the trial as a result of the delayed stimulation onset. So far there was no obvious conflict between the experimental results and the expectations raised by the indirect-involvement model. It is interesting now to surmise what one might expect on the basis of this hypothesis if the monkey already started the movement to the target before the E-stimulus is applied.

E-PERTURBATION OF V-TRIGGERED 3D RESPONSES. In the case of saccades, it was well established that E-stimulation in midflight causes a perturbing effect on the V-guided response (Schlag-Rey et al. 1989). In other words, a full-blown saccade response will only be observed if the E-stimulus is delayed until after saccade completion. This is also evident from our data presentation in Fig. 10*A*. If we stimulated earlier, we observed that the saccade only reached roughly halfway completion by the time the V-latency range was reached. Not only does the saccade response intersect the zero latency axis far below V-control level (see Fig. 10*A*) but it continues to be influenced by the E-stimulus when the response is V-guided.

Of crucial importance is how the depth components are affected. The indirect involvement model predicts that, when E-latencies are close to zero (i.e., when the E-stimulus occurs roughly in the V-latency range), one should see a complete vergence response that is equal to the V-control response. Because the SC, according to this model, has no metrical vergence signal there is no reason to expect any change in the vergence response if E-stimulation is applied in midflight. Such a situation would be in stark contrast to the scenario sketched previously for the saccadic system. Our results show instead that V-initiated EV-movements show equally strong perturbation effects in both vergence and saccade-related movements so that the indirect involvement model must be abandoned. At zero E-latency, the intrasaccadic vergence displacement is far less than what was seen during the V-controls (see Fig. 10*B*). Furthermore, the distribution of the vergence data points exhibits striking similarities to that seen for the saccade responses, indicating that neither the saccadic nor the depth responses are full blown even when the V-guided responses begin. The data points in Fig. 11 indicate that if the saccadic system is highly perturbed then so is the vergence system, regardless of site location. The results show that the data points that are associated with negative E-latencies remain a part of the continuum that makes up the transition between the two sets of controls. Clearly the axis of zero latency is not a cutoff point, and the two sets of stimuli (E and V) still continue with a weighted competition during V-guided EV-responses as they did previously for the E-triggered EV-trials. A further finding of interest is that the strong relationship between the saccade and vergence metrics is not entirely due to the latency dependence seen in Fig. 10. It appears that the high correlation between the two components, shown on a trial-by-trial basis in Fig. 12, partly reflects the presence of a common noise source. These data along with evidence that the results are not indirectly due to duration artifacts (Table 2) provide strong support for a direct involvement model approach.

Direct involvement model

It has become clear that the explanation put forward previously by Glimcher and Sparks (1993), on how combined EV-stimulation leads to a compromise between competing signals in the frontal plane, can be extended to the realm of 3D space. How these newly found temporal and metrical effects can be reconciled with the direct involvement model will now be discussed.

To understand what this means we must consider that the SC may actually be involved in the coding of 3D information. However, it does appear difficult at first glance to reconcile this notion with the zero-vergence response obtained during E-controls. As a prelude to a discussion on how this issue may be resolved, we provide an overview of the classical collicular scheme and subsequently present suggestions on possible revisions of this model.

Indirect evidence for 3D colliculus

The SC was always considered to be a saccadic control center receiving input signals from 2D neural structures and projecting information to regions that handled conjugate signals. This picture was modified somewhat lately, on the basis of new studies that shed new light on 3D information processing, upstream and downstream of the SC. We present some of this evidence.

Signals reflecting stimulus location in 3D space were found not only in various regions of the monkey visual cortex (for review see Trotter 1995) but also in the parietal cortex (Colby et al. 1993; DeAngelis et al. 1998; Roy et al. 1992; Sakata et al. 1997). The lateral intraparietal area (LIP) has cells with 3D tuning curves (Gnadt and Mays 1995), and it was demonstrated that these "saccade-related" neurons, tuned for a 3D volume of space, project depth-related as well as directional information to the SC (Gnadt and Beyer 1998). Although it has long been known that the SC of the cat has a large proportion of binocular cells (Berman et al. 1975), it is only since very recently that a systematic study was done to determine that cells in the superficial layers of the cat SC can have binocular receptive fields with various types of coarse disparity–sensitivity profiles (Bacon et al. 1998). Dias et al. (1991) previously reported on broadly tuned disparity–selectivity in the superficial layers of the SC of the opossum. Because binocular disparity provides one of the principal cues for converting the 2D retinal images into a 3D percept, these studies suggest that the SC has access to vital information for mediating vergence eye movements.

Although it may come as a surprise to learn that the SC, often portrayed as a bastion of saccadic control, may have a broader role, there is reason to think that the same may apply to so-called saccadic burst cells downstream of the SC. A recent neurophysiological study (Zhou and King 1998) has shown, in a radical departure from the classical scheme of separate saccadic and vergence control systems, that binocular fast eye movements may be controlled separately for each eye. They show that saccadic burst cells at the premotor level, previously thought to code conjugate signals, are actually monocular in nature. This indicates that the idea of a binocular version and vergence system is probably oversimplified. It now appears that depth movements could be attributed at least partly to unequal saccades caused by a disconjugate saccadic control of each eye separately. This new finding, that the population of burst cells contains a 3D code, raises interesting questions about the SC, which is a major source of input to this population and is classically regarded as a 2D structure. We

propose that this may be less of an enigma if the SC also contains a 3D code (see Fig. 1*C*), a possibility that finds strong support in this paper.

Further support was provided by recent findings that relate the SC to changes in accommodation. This is interesting because accommodation and vergence control are considered to be closely related (Carpenter 1988). Sawa and Ohtsuka (1994) reported an increase in accommodation when the rostral collicular region in the anesthetized cat was stimulated. An anatomic study established, furthermore, that rostral neurons project to accommodation-related areas (Sato and Ohtsuka. 1996). More recently, Billitz and Mays (1997), in the monkey, elicited a relaxation in accommodation, and they observed divergence response when microstimulation was applied in the deeper layers throughout the colliculus, during a near fixation task. Another interesting study indicated that the rostral area of the SC in the alert cat contains neurons that are modulated (i.e., the cell discharge pauses or increases) during vergence eye movements (Jiang et al. 1996). E-stimulation in the deeper layers of the cat rostral SC was reported to induce disconjugate eye movements and even pure vergence (Jiang et al. 1996).

Whether the newly discovered vergence effects described in this paper are a direct reflection of signal processing inside the SC or whether they arise indirectly cannot be determined at this moment. Assuming the former, we now discuss a hypothetical collicular coding scheme that seems to allow a simple interpretation of our findings.

3D movement coding scheme for colliculus

The SC is commonly divided into superficial and deeper layers. Although neurons in the superficial layers are activated by visual stimuli in their receptive field, neurons in the deeper layers are mainly involved in orienting eye movements. The latter only fire for eye movements into their movement field that delineates the range of saccade vectors for which a particular cell is activated. Movement fields are topographically laid out in a motor map, and suprathreshold E-stimulation at a specific point elicits saccades with reproducible vectors, a specific amplitude and direction but no depth component. We now propose how this model can be revised, considering the recent literature and our experimental data.

Gnadt and Beyer (1998) described depth-related signals carried from area LIP to the SC. This suggests that deeper layer movement cells have access to depth information that is needed to code eye movements in 3D space. Each specific location in the motor map of the SC contains a group of movement cells that share the same direction preference (in the frontal plane). We propose a new scenario where they would also have a preferred depth component, different for each cell. Thus, if within this group the neurons are randomly intermingled (no topographical code for depth, only for direction), then it becomes quite straightforward to understand that any indiscriminate activation by local E-stimulation yields a fixed 2D (horizontal and vertical components) saccade vector but a net depth command signal that equals zero. The latter should not be confused with simply the absence of a vergence signal.

To directly relate this hypothesis to our results we refer to the scheme shown in Fig. 14. In the classical picture of a 2D colliculus, site X is activated by E-stimulation and leads to a saccade that is directed upward. Cells at site Y are excited when a saccade of similar amplitude is made in the downward direction toward the location of the V-stimulus (Van Gisbergen et al. 1987). In the case of simultaneous E- and V-activation a compromise response occurs, which can be thought of as the result of a weighted average of the two sets of signals that were built up at the different sites thus far. The result is a saccade that is directed somewhere between the E- and the V-saccades, depending on the timing of the E-stimulus, and its current strength.

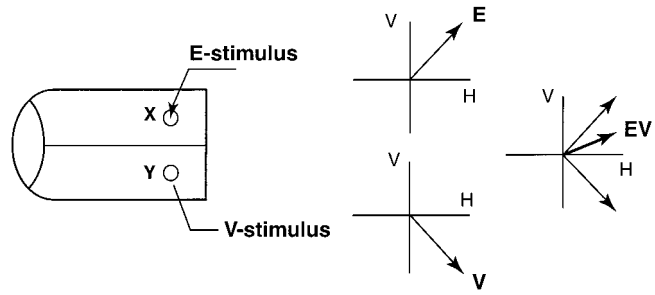

FIG. 14. Classical model of 2D movement coding by the SC. By stimulating at a specific site X, an E-saccade can be evoked with a fixed amplitude and direction in the frontal plane. When a V-guided eye movement to a nearby target is elicited that requires a saccade with roughly the same amplitude but a different direction, cells at site Y are activated that code only the horizontal and vertical components of the 3D refixation. An EV-response obtained by stimulating site X shortly after presenting the V-target will show an intermediate saccade. This will be a weighted average of the 2 saccade vectors, depending on the time delay between target onset and stimulation onset.

The new idea of a 3D colliculus is presented in a similar way in Fig. 15. The two sites are activated in the same fashion as described for the 2D situation. Additionally, however, each neuron codes for its own preferred depth. The broad distribution of depth vectors, with an evenly ordered range of converging and diverging components, is shown for both sites X and Y (Fig. 15*A*). In the next step (Fig. 15*B*) we depict what would happen during control situations and combined EV-responses. The horizontal and vertical components of the controls are identical with the classical situation. However, if, based on population coding, a weighted average is taken of all the depth directions coded by the population of cells at location X, as would be expected during E-stimulation, then one would obtain a zero-vergence signal. This desired zero-vergence command can cause vergence perturbation unlike the 2D colliculus. As explained in Fig. 15, *far-right bottom diagram*, the final outcome in EV-responses would again be a weighted average of the signal carried by the population of E-activated neurons and the population of V-activated cells, just as was described for the case of direction (the saccadic component). The latter set of cells provides for the occurrence of a locally represented saccade vector and a vergence component that enables the eyes to fixate the near target. The population of E-activated cells emphatically demands a 3D movement with zero vergence, and it is this insistence on a zero-vergence movement that, according to the proposal, causes the disturbance in the vergence component of EV-responses.

It is interesting that Gnadt and Beyer (1998) left open this possibility of a 3D colliculus as a consequence of their findings that area LIP neurons send depth-related signals to the SC. They briefly mention that previous studies may not have adequately tested for this possibility and that E-stimulation at a particular site may "recruit neurons across a range of depth sensitivities that are embedded within the map." It is clear that only single-unit studies showing that SC movement cells are

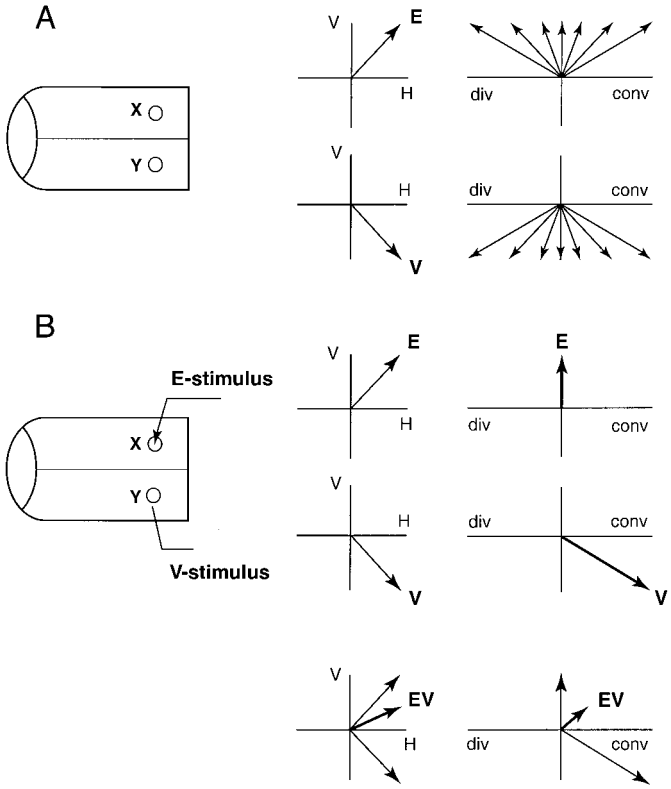

FIG. 15. New collicular model proposing that cells code for a 3D movement vector, i.e., in direction and depth. *A*: cells at site X and site Y are activated for saccades in 2D, but each cell now has its own preferred depth component. The entire population of cells at each respective site will therefore cover the entire spectrum of depth space (from diverging to converging movements of varying amplitudes) for that saccade vector. *B*: when an E-stimulus is applied at site X, the same saccade is elicited as in the old scheme of Fig. 14. However, now, as a result of population coding, an average will be taken of the entire group of cells resulting in a 0-vergence command. On presentation of the V-stimulus at different depths the appropriate 3D cells at site Y are excited. For an EV-response, a similar weighted compromise is seen as in the 2D model for the saccadic component. Additionally a vergence component compromise will emerge that is also a weighted average of the separate E- and V-responses.

actually tuned in depth will provide clarification, and in the absence of these results the present interpretation of our findings can only be preliminary.

Further evaluation of 3D colliculus model

It is interesting to reflect for a moment on two other aspects of the results that were not yet discussed in terms of the model. First, we found that the perturbation effects varied in strength from site to site but were generally approximately equal for the saccade and vergence component (see Fig. 11). If, depending on the position of the electrode and on current intensity, the strength of the E-vector signal varies from site to site, this will have similar consequences for its direction and its depth component. It is this vector strength that will determine the perturbation effect in the weighted averaging process that also takes into account the V-vector. Similarly, the V-vector will have its direction fixed by the location of the target but its strength will be time dependent, varying with the time since target onset. It is quite feasible that the time course of this buildup may vary somewhat from trial to trial, thereby causing a fluctuation around the mean behavior. In this way, it can be understood, in principle, why the trial-to-trial variability was to a considerable extent common to the saccadic and the vergence component (see Table 2). If the specification of the saccade and vergence components would take place at different centers, such couplings would be less easy to comprehend.

Indirect support for the idea of a vergence-related colliculus comes from a study where the midbrain was damaged (Lawler and Cowey 1986). Monkeys with large collicular lesions were observed to have a dramatic misalignment of their visual axes, suggesting diplopia. It was suggested that the perceptual impairments that followed as a consequence of this pathology were due to faulty vergence eye movements. Of course, one cannot exclude the possibility that these lesions indirectly affected other neural regions that may have been involved in vergence control.

As mentioned previously, decisive evidence to test our hypothesis will have to come from single-unit studies that investigate depth-related activity in the deeper layers of the SC. To our knowledge there was until now only one preliminary study on the question as to whether SC burst neurons are involved in vergence control (Mays 1996). Initial results appear to indicate that firing rates are modified when convergence components occur in conjunction with saccades. It is not clear as yet whether that is due to a change in the velocity of the 3D response, compared with similar amplitude saccades in the frontal plane, or whether the SC is truly involved in coding depth movements.

CONCLUSION

The neurophysiological perturbation experiments revealed two distinct effects of SC-stimulation on vergence in the presence of a V-target, involving the initiation (WHEN) and the metric-specification (WHERE) systems that were not expressed when E-stimulation was applied in isolation. Although our results are partly compatible with the notion of a common gating system to saccades and vergence, it is clear that this is not an elaborate-enough scheme to explain all the previously described phenomena. To make better sense of the results, we interpret the absence of an overt vergence effect on E-stimulation in the SC as a command specifying a zero-vergence change rather than as the mere absence of a vergence signal. In the perturbation trials, this zero signal competes with the V-related vergence signal, thereby causing a perturbation with averaging characteristics. This effect would be expected if the population of movement cells at each SC site is tuned in 3D, combining the well-known topographical code for direction with a nontopographical depth representation. On E-stimulation, the local population would yield a net saccade signal because of the topography, but the cells coding for different depths would be excited equally, causing the vergence change to be zero.

We thank S. Gielen for providing useful comments and F. van der Werf for doing the histology. We gratefully acknowledge the experimental and technical assistance of C. van der Lee, T. van Dreumel, H. Kleijnen, V. Langeveld, G. van Lingen, and W. Corbeek. We also thank H. Arndts, M. Faassen, A. Peters, and F. Philipsen for animal care.

This study was supported by the Foundation for Life Sciences and the Netherlands Organization for Scientific Research.

Address for reprint requests: J.A.M. Van Gisbergen, 231 Dept. of Medical Physics and Biophysics, University of Nijmegen, P.O. Box 9101, 6500HB Nijmegen, The Netherlands.

Received 28 September 1998; accepted in final form 13 January 1999.

REFERENCES

BACON, B. A., VILLEMAGNE, J., BERGERON, A., LEPORE, F., AND GUILLEMOT, J.-P. Spatial disparity coding in the superior colliculus of the cat. *Exp. Brain Res.* 119: 333–344, 1998.

BECKER, W. AND JURGENS, R. An analysis of the saccadic system by means of double step stimuli. *Vision Res.* 19: 967–983, 1979.

BERMAN, N., BLAKEMORE, C., AND CYNADER, M. Binocular interaction in the cat's superior colliculus. *J. Physiol. (Lond.).* 246: 595–615, 1975.

BILLITZ, M. S. AND MAYS, L. E. Effects of microstimulation of the superior colliculus on vergence and accomodation (Abstract). *Invest. Ophthalmol. Vis. Sci.* 38, *Suppl*.: 984, 1997.

BOUR, L. J., VAN GISBERGEN, J.A.M., BRUIJNS, J., AND OTTES F. P. The double magnetic induction method for measuring eye movements: results in monkey and man. *IEEE Trans. Biomed. Eng.* 31: 419–427, 1984.

BUTTNER-ENNEVER, J. A. AND HORN, A.K.E. Neuroanatomy of saccadic omnipause neurons in nucleus raphe interpositus. In: *Contemporary Ocular Motor and Vestibular Research: A Tribute to David A. Robinson*, edited by A. F. Fuchs, T. Brandt, U. Buttner, and D. S. Zee. Stuttgart: Thieme, 1994, p. 488–495.

CARPENTER, R.H.S. *Movements of the Eyes* (2nd ed.). London: Pion, 1988.

CHATURVEDI, V. AND VAN GISBERGEN, J.A.M. Shared target selection for combined version-vergence eye movements. *J. Neurophysiol.* 80: 849–862, 1998.

COLBY, C. L., DUHAMEL, J.-R., AND GOLDBERG, M. E. Ventral intraparietal area of the macaque: anatomic location and visual response properties. *J. Neurophysiol.* 69: 902–914, 1993.

COLLEWIJN, H., ERKELENS, C. J., AND STEINMAN, R. M. Binocular co-ordination of human horizontal saccadic eye movements. *J. Physiol. (Lond.)* 404: 157–182, 1988.

COLLEWIJN, H., ERKELENS, C. J., AND STEINMAN, R. M. Voluntary binocular gaze-shifts in the plane of regard: dynamics of version and vergence. *Vision Res.* 35: 3335–3358, 1995.

DEANGELIS, G. C, CUMMING, B. G., AND NEWSOME, W. T. Cortical area MT and the perception of stereoscopic depth. *Nature* 394: 677–679, 1998.

DIAS, E. C., ROCHA-MIRANDA, C. E., BERNARDER, R. F., AND SCHMIDT, S. L. Disparity selective units in the superior colliculus of the opossum. *Exp. Brain Res.* 87: 546–552, 1991.

ENRIGHT, J. T. Changes in vergence mediated by saccades. *J. Physiol. (Lond.)* 350: 9–31, 1984.

ENRIGHT, J. T. Facilitation of vergence changes by saccades: influences of misfocused images and of disparity stimuli in man. *J. Physiol. (Lond.)* 371: 69–87, 1986.

ERKELENS, C. J., STEINMAN, R. M., AND COLLEWIJN, H. Ocular vergence under natural conditions. II. Gaze shifts between real targets differing in distance and direction. *Proc. R. Soc. Lond. B Biol. Sci.* 236: 441–465, 1989.

GANDHI, N. J. AND KELLER, E. L. Spatial distribution and discharge characteristics of monkey superior colliculus neurons antidromically activated from the omnipause region in monkey. *J. Neurophysiol.* 78: 2221–2225, 1997.

GLIMCHER, P. W. AND SPARKS, D. L. Movement selection in advance of action in the superior colliculus. *Nature.* 355: 542–545, 1992.

GLIMCHER, P. W. AND SPARKS, D. L. Effects of low-frequency stimulation of the superior colliculus on spontaneous and visually guided saccades. *J. Neurophysiol.* 69: 953–964, 1993.

GNADT, J. W. AND BEYER, J. Eye movements in depth: What does the monkey's parietal cortex tell the superior colliculus. *NeuroReport* 9: 233–238, 1998.

GNADT, J. W. AND MAYS, L. E. Neurons in monkey parietal area LIP are tuned for eye-movement parameters in three-dimensional space. *J. Neurophysiol.* 73: 280–297, 1995.

JIANG, H., GUITTON, D., AND CULLEN, K. E. Near-response-related neural activity in the rostral superior colliculus of the cat. *Soc. Neurosci. Abstr.* 22: 662, 1996.

JUDGE, S. J. AND CUMMING, B. G. Neurons in the monkey midbrain with activity related to vergence eye movement and accommodation. *J. Neurophysiol.* 55: 915–930, 1986.

JUDGE, S. J., RICHMOND, B. J., AND CHU, F. C. Implantation of magnetic search coils for measurement of eye position; an improved method. *Vision Res.* 20: 535–538, 1980.

LAWLER, K. A. AND COWEY, A. The effects of pretectal and superior colliculus lesions on binocular vision. *Exp. Brain Res.* 63: 402–408. 1986.

MALPELI, J. G. Measuring eye position with the double magnetic induction method. *J. Neurosci. Methods* 86: 55–61, 1998.

MAYS, L. E. Neural control of vergence eye movements: convergence and divergence neurons in midbrain. *J. Neurophysiol.* 51: 1091–1108, 1984.

MAYS, L. E. Activity of superior colliculus burst neurons during saccade-vergence interactions. *Soc. Neurosci. Abstr.* 22: 664, 1996.

MAYS, L. E. AND GAMLIN, P.D.R. Neuronal circuitry controlling the near response. *Curr. Opin. Neurobiol.* 5: 763–768, 1995.

MAYS, L. E. AND GAMLIN, P.D.R. A neural mechanism subserving saccade-vergence interactions. In: *Eye Movement Research: Mechanisms, Processes and Applications*, edited by J. Findlay, R. Walker, and R. W. Kentridge. Amsterdam: Elsevier, 1996, p. 215–223.

MAYS, L. E., PORTER, J. D., GAMLIN, P.D.R., AND TELLO, C. A. Neural control of vergence eye movements: neurons encoding vergence velocity. *J. Neurophysiol.* 56: 1007–1021, 1986.

MAYS, L. E. AND SPARKS, D. L. Dissociation of visual and saccade-related responses in superior colliculus neurons. *J. Neurophysiol.* 43: 207–232, 1980.

MAXWELL, J. S. AND KING, W. M. Dynamics and efficacy of saccade-facilitated vergence eye movements in monkeys. *J. Neurophysiol.* 68: 1248–1260, 1992.

MELIS, B.J.M. AND VAN GISBERGEN, J.A.M. Short-term adaptation of electrically induced saccades in monkey superior colliculus. *J. Neurophysiol.* 76: 1744–1758, 1996.

MUNOZ, D. P. AND WURTZ, R. H. Saccade-related activity in monkey superior colliculus II. Spread of activity during saccades. *J. Neurophysiol.* 73: 2334–2348, 1995.

OOHIRA, A. Vergence eye movements facilitated by saccades. *Jpn. J. Ophthalmol.* 37: 400–413, 1993.

RAYBOURN, M. S. AND KELLER, L. E. Colliculoreticular organization in primate oculomotor system. *J. Neurophysiol.* 40: 861–878, 1977.

ROBINSON, D. A. Eye movements evoked by collicular stimulation in the alert monkey. *Vision Res.* 12: 1795–1808, 1972.

ROY, J.-P., KOMATSU, H., AND WURTZ, R. H. Disparity sensitivity of neurons in monkey extrastriate area MST. *J. Neurosci.* 12: 2478–2492, 1992.

SAKATA, H., TAIRA, M., KUSUNOKI, M., MURATA, A., AND TANAKA, Y. The parietal association cortex in depth perception and visual control of hand action. *Trends Neurosci.* 20: 350–357, 1997.

SATO, A. AND OHTSUKA, K. Projection from the accommodation-related area in the superior colliculus of the cat. *J. Comp. Neurol.* 367: 465–476, 1996.

SAWA, M. AND OHTSUKA, K. Lens accommodation evoked by microstimulation of the superior colliculus in the cat. *Vision Res.* 34: 975–981, 1994.

SCHILLER, P. H. AND STRYKER, M. Single-unit recording and stimulation in superior colliculus of the alert rhesus monkey. *J. Neurophysiol.* 35: 915–924, 1972.

SCHLAG-REY, M., SCHLAG, J., AND SHOOK, B. Interactions between natural and electrically-evoked saccades. I. Differences between sites carrying retinal error and motor error signals in monkey superior colliculus. *Exp. Brain Res.* 76: 537–547, 1989.

SPARKS, D. L. Functional properties of neurons in the monkey superior colliculus: coupling of neuronal activity and saccade onset. *Brain Res.* 156: 1–16, 1978.

SPARKS, D. L., HOLLAND, R., AND GUTHRIE, B. L. Size and distibution of movement fields in the monkey superior colliculus. *Brain Res.* 113: 21–34, 1976.

SPARKS, D. L. AND MAYS, L. E. Movement fields of saccade-related burst neurons in the monkey superior colliculus. *Brain Res.* 190: 29–50, 1980.

SPARKS, D. L. AND MAYS, L. E. Spatial localization of saccade targets. I. Compensation for stimulation-induced perturbations in eye position. *J. Neurophysiol.* 49: 45–63, 1983.

TROTTER, Y. Cortical representation of visual three-dimensional space. *Perception* 24: 287–298, 1995.

VAN GISBERGEN, J.A.M., VAN OPSTAL, A. J., AND TAX, A.A.M. Collicular ensemble coding of saccades based on vector summation. *Neuroscience* 21: 541–555, 1987.

WURTZ, R. H. Vision for the control of movement. The Friedenwald Lecture. *Invest. Ophthalmol. Vis. Sci.* 37: 2131–2145, 1996.

WURTZ, R. H. AND GOLDBERG, M. E. Activity of superior colliculus in behaving monkey. III. Cells discharging before eye movements. *J. Neurophysiol.* 35: 575–586, 1972.

YARBUS, A. L. *Eye Movements and Vision*. New York: Plenum, 1967.

ZEE, D. S., FITZGIBBON, E. J., AND OPTICAN, L. M. Saccade-vergence interactions in humans. *J. Neurophysiol.* 68: 1624–1641, 1992.

ZHOU, W. AND KING, W. M. Premotor commands encode monocular eye movements. *Nature* 393: 692–695, 1998.