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VELOCITY STORAGE IN VERTICAL OPTOKINETIC AND VESTIBULAR NYSTAGMUS AND VISUAL-VESTIBULAR INTERACTION

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VELOCITY STORAGE IN VERTICAL OPTOKINETIC AND VESTIBULAR NYSTAGMUS AND VISUAL-VESTIBULAR INTERACTION

by

Victor Matsuo

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

1981

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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Abstract

VELOCITY STORAGE IN VERTICAL OPTOKINETIC AND VESTIBULAR NYSTAGMUS AND VISUAL-VESTIBULAR INTERACTION

by

Victor Matsuo

Advisor: Professor Bernard Cohen

Vertical optokinetic and vestibular nystagmus were recorded in 9 monkeys. Eye movements were recorded using silver silver-chloride EOG electrodes and direct coupled amplifiers. The EOG was electronically differentiated and rectified to get slow phase velocities of nystagmus. Monkeys were tested lying on their sides. Steps of full field optokinetic and/or vestibular stimulation were given at velocities from 10 to 180 deg/sec.

Downward nystagmus was always more prominent than upward nystagmus. Downward OKN reached higher velocities than upward OKN did, and downward OKAN was more vigorous, saturating at about 45 deg/sec. Upward OKAN was weak or absent, and group mean values did not exceed 10 deg/sec. Peak velocities of vertical vestibular nystagmus induced by rotation in darkness were symmetrical, but time constants of downward nystagmus were longer than those of upward nystagmus (12 to 16 sec vs 5 to 10 sec). Exposure to a stationary surround (visual suppression) was less effective in suppressing downward vestibular nystagmus than upward nystagmus. Time constants of visual suppression of downward vestibular nystagmus were about 8 sec. This is in contrast to time constants of visual suppression of upward nystagmus which were about 3.5 sec.

The asymmetry in vertical nystagmus was also seen during visual-vestibular interactions. After rotation in light that evoked downward nystagmus, animals were halted in darkness. Downward OKAN summed with upward post rotatory nystagmus and cancelled the after response. As a result, little or no after nystagmus was seen. Rotation in the opposite direction evoked upward OKN. Since upward OKAN was weak or absent, at the end of stimulation downward post rotatory nystagmus was unopposed and was as strong as post rotatory nystagmus recorded after rotation in darkness. When the optokinetic input was altered, the after responses increased or decreased over a range that was limited only by the saturation velocities of upward and downward OKAN. The results were interpreted in terms of a model of optokinetic and vestibular nystagmus generation that includes a velocity storage integrator. The degree of velocity storage during downward nystagmus was comparable to that during horizontal nystagmus. In contrast, there was little or no evidence of velocity storage during upward nystagmus.

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I. Introduction.

Movement of the head in light is normally accomplished without blurring of vision. This is due to the action of a neural mechanism that moves the eyes in the plane of head rotation, at the same velocity but in the opposite direction to head movement. These eye movements, which compensate for head movements, are generated in the vestibulo-ocular reflex (VOR). Both optokinetic and vestibular information are used to produce the overall response. The description of the time domain behavior of these complementary responses, and the way that they combine to produce vertical nystagmus, is the focus of the present investigation.

Theoretical background.

A mathematical model of optokinetic and vestibular nystagmus generation was formulated by Raphan and colleagues on the basis of data from studies of horizontal OKN, OKAN, vestibular nystagmus and visual vestibular interactions (Cohen, Matsuo and Raphan, 1977; Raphan, Matsuo and Cohen, 1977, 1979). The model includes "direct" visual and vestibular pathways that carry information about head or environmental velocity, and an integrator, common to both visual and vestibular pathways, that stores activity related to slow phase eye velocity. The sum of these elements provides the velocity command to drive the eyes. Since considerable emphasis will be placed on the integrator in this thesis, its theoretical basis will be considered first.

The integrator referred to in this report is a neural network that behaves like a nonideal, or "leaky," integrator (Raphan and Cohen, 1981). For a stepwise increase in input level, the state of a nonideal integrator changes by rising exponentially to a new value. If the input step is sufficiently long, a saturation level is reached in the state of the integrator that represents an equilibrium between the steady state input and the loss of charge on the integrator, i.e., the "leak." When the input goes to zero, the state of the integrator does not go to zero immediately, but approaches the zero level exponentially. In response to an impulsive input, the state of the integrator increases with its characteristic time constant and then starts to fall slowly after the impulse is over. Because the state of a nonideal integrator returns to zero slowly after the input has gone to zero, it has stored information related to the input. The rate of decay of the stored information depends on the time constant of the integrator. In the Raphan model, the input to the integrator is the velocity of the head or environment derived from the end organs of the vestibular or visual system. Since the integrator is postulated to store information related to the velocity of the head or visual surround, and since its output forms part of the slow phase velocity command to drive the eyes, it has been referred to as a "velocity storage integrator," and the information it stores is referred to as "stored velocity." A more complete description of the integrator appears elsewhere (Cohen, et al., 1977; Raphan et al., 1977, 1979; Raphan and Cohen, 1980, 1981).

Although "storage of velocity" is a hypothetical concept, it accounts for the characteristics of nystagmus slow phase velocity observed in the course of the above investigations and in the present experiments. It implicitly assumes that one or more neuronal networks responsible for driving the eyes during slow phases of nystagmus is activated during optokinetic and vestibular stimulation, and retains a level of activity related to slow phase velocity. Although the identification of cell groups and neural networks performing the integration is incomplete, the concept has a physical reality since evidence of stored velocity information is found in the firing rates of cells in the vestibular nuclei (Waespe and Henn, 1977a,b, 1978a,b). Several lines of evidence indicate that the state of the storage integrator is intimately associated with the VOR (see below). Thus, although the cellular basis for velocity storage is not yet completely understood, it will be assumed that the integration is performed by cellular groups within the VOR.

Rationale.

The present work was done to describe the characteristics of velocity storage related to vertical nystagmus. Preliminary results have suggested that although horizontal velocity storage is left-right symmetrical, vertical nystagmus is markedly asymmetrical, there being considerably more velocity storage during downward nystagmus than upward nystagmus (Matsuo, Cohen, Raphan, de Jong and Henn, 1979). An asymmetry in vertical OKN had been noted before in various studies (Krieger and Bender, 1956; Pasik, Pasik and Bender 1969; Pasik, Pasik, Valciukas and Bender, 1971; Koempf, Pasik, Pasik and Bender, 1979). It had also been seen during vestibular nystagmus (Mygind, 1925; Money and Scott, 1962; Collins and Guedry, 1967; Koempf et al., 1979), but these reports described the responses qualitatively. A parametric study of vertical optokinetic responses was attempted by Takahashi and Igarashi (1977), but OKAN was only partially described.

The first goal of this research was to determine whether there is evidence for velocity storage during vertical vestibular and optokinetic nystagmus (OKN), and if so, to measure it. In addition, it would be useful to determine the dynamic characteristics of the stored activity related to vertical eye velocity by measuring the time constants of charge and discharge of the storage mechanism using techniques similar to those used for horizontal nystagmus (Cohen et al., 1977; Raphan et al., 1979). This would permit a comparison of the characteristics of velocity storage in the horizontal and vertical planes. Finally, visual-vestibular interaction in the vertical plane has not been extensively tested yet, nor have the dynamic characteristics of velocity storage during vertical nystagmus interactions been ascertained. These data would be useful in formulating a model of vertical nystagmus and would help provide a further understanding of the organization of the vestibular and oculomotor systems.

Background.

During head movement in light, as the head moves in one direction there is relative motion of the visual surround in the opposite direction. If the image of the visual surround is held stationary on the retina, the surround is seen more clearly. This can be accomplished by moving the eyes in the direction of environmental motion at approximately the velocity of field movement so as to compensate for head movement. Compensatory eye movements are evoked during movement of the head by activation of the vestibulo-ocular reflex (VOR) (Dodge, 1903, 1923; Dusser de Barenne, 1934), using both visual and vestibular information. The vestibular contribution to the horizontal VOR has been studied in a wide variety of species. See Cohen (1971, 1974) and Wilson and Melvill Jones (1979) for recent reviews. Less is known about the vertical VOR although it also has been investigated in several species including rabbits (Barmack, in press), cats (Money and Scott, 1962; Collins and Guedry, 1967), monkeys, (Evinger, Fuchs and Baker, 1977) and humans (Melvill Jones, Barry and Kowalsky, 1964; Benson and Bodin, 1966; Collins and Guedry, 1967; Guedry and Benson, 1971). The visual contribution, expressed as optokinetic nystagmus (OKN), has also been extensively studied in a wide range of species including monkeys (Ter Braak, 1936; Krieger and Bender, 1956; Pasik and Pasik, 1964; Komatsuzaki, Harris, Alpert and Cohen, 1969; Koerner and Schiller, 1972; Valciukas, 1972; Cohen, Uemura and Takemori, 1973; Valciukas, Pasik and Pasik, 1973; Buettner, Waespe and Henn, 1976; Takahashi and Igarashi, 1977; Takahashi, Igarashi and Homick, 1977; Waespe and Henn, 1977b; Waespe and Henn, 1978a; Waespe, Henn and Isoviita, 1980), and humans (Ohm, 1922; Fox and Dodge, 1929; Dodge, Travis and Fox, 1930; Gruettner, 1939; Jung, 1948; Collins et al., 1970; Honrubia, Downey, Mitchell and Ward, 1968; Takahashi, Sakurai and Kanzaki, 1978). In this review the origin and characteristics of vestibular and visual activity used to produce compensatory eye movements will be briefly considered, along with evidence that suggests that a storage mechanism located in the VOR contributes to the production of compensatory movements. The vestibulo-ocular reflex arc (VOR) is the term used to describe the neuronal subsystem that links the vestibular receptors and the extraocular muscles (Lorente de No, 1933; Szentagothai, 1950).

Vestibular contributions to the VOR.

The semicircular canals respond to angular acceleration, but due to the dynamics of the cupula and endolymph, there is a mechanical integration within the canal. Consequently, the frequency of firing in the vestibular nerve is proportional to head angular velocity, not to angular acceleration, in the range of normal head movements (Adrian, 1943; Fernandez and Goldberg, 1971; Goldberg and Fernandez, 1971). The head velocity signal coming from the canals is integrated twice more before it reaches eye muscle motoneurons. The first of these integrations appears to be in the vestibular system, and causes prolongation of the velocity signal coming from the vestibular end organ. This integrator is also responsible for storing activity during OKN that is expressed as OKAN (Cohen et al., 1977; Raphan et al., 1977, 1979; Raphan and Cohen, 1980, 1981). The other integrator is the velocity to position integrator that converts the velocity signal coming from the vestibular system to a position signal to drive the eye muscle motoneurons (Skavenski and Robinson, 1973; Robinson, 1974, 1975). The neural integrator in this report refers to the velocity storage integrator, not the velocity to position integrator.

The mechanical integration at the end organ is nonideal, that is, the integrator has a continuous loss of charge during a steady input. Consequently, activity in the vestibular nerve continuously declines during rotation at a constant velocity. The time constant of this decline is about 5 sec in the monkey (Fernandez and Goldberg, 1971; Fernandez and Goldberg, 1971). This results in an inappropriate signal coming from the labyrinths during constant velocity rotation. If the head moves at a constant rate, the semicircular canals indicate that head velocity is declining, and finally that it has stopped, although it is still in motion. The nervous system has several ways to overcome this apparent misinformation, utilizing both vestibular and visual information.

In response to a step in velocity, although the time constant of activity in the vestbular nerve is 5 seconds, the time constant of horizontal vestibular nystagmus in the dark is 15 to 30 sec (Cohen et al., 1977; Raphan et al., 1977, 1979). The persistence of nystagmus beyond the increase in activity in the VIIIth nerve appears to be due to a central neural network that is charged by peripheral nerve activity. It slowly dissipates its charge at the end of stimulation, producing nystagmus with steadily diminishing velocity (Mowrer, 1934; Cohen et al., 1977; Raphan et al., 1977, 1979). This neural network that functions as an imperfect integrator improves the low frequency characteristics of the VOR by prolonging the time over which vestibularly induced nystagmus is evoked during constant velocity rotation (Robinson, 1976). Even with this "velocity storage" integrator, however, rotation in darkness that lasts longer than 10 sec evokes nystagmus that is not fully compensatory (Dodge, 1923; Raphan et al., 1979). This is corrected by combining OKN with vestibular nystagmus (Ter Braak, 1936; Mowrer, 1937; Rademaker and Ter Braak, 1948; Raphan et al., 1979; Matsuo et al., 1979).

Optokinetic contributions to the VOR.

The characteristics of optokinetic and vestibular nystagmus complement each other. Vestibular nystagmus responds quickly to step changes in head velocity but has a poor sustained response. Optokinetic nystagmus has an effective sustained response to velocity step inputs but does not immediately approximate the velocity of the moving surround. During constant velocity rotations in light, the nystagmus appears as though it were initiated by the vestibular response and sustained by the optokinetic response (Dodge, 1923; Ter Braak, 1936; Rademaker and Ter Braak, 1948; Raphan et al., 1979).

There are prominent after responses following both vestibular stimulation in darkness and full field optokinetic stimulation. These responses are known as post rotatory nystagmus and optokinetic after nystagmus (OKAN). They have approximately the same duration but are in opposite directions. Vestibular post rotatory nystagmus is initiated by the deflection of the cupula during the impulse of acceleration at the end of the velocity step. OKAN is due to activity that is stored during OKN and discharged after the end of stimulation (Cohen et al., 1977). When an animal is stopped after rotating at a constant velocity in light, there is little or no after response that corresponds to OKAN or post rotatory nystagmus (Ter Braak, 1936; Mowrer, 1937; Rademaker and Ter Braak, 1948; Raphan et al., 1979; Matsuo et al., 1979). This result can be explained by assuming that activity responsible for OKAN and post rotatory nystagmus, evoked simultaneously at the end of rotation, had cancelled each other. Thus, although OKAN and post rotatory responses appear to be anticompensatory because they are nystagmic eye movements that occur when neither the head nor the field was moving any longer (Dodge, 1923), they are functionally compensatory since they cancel each other to reduce nystagmus at the end of rotation in light.

The present report is restricted to a description of primary OKAN, which immediately follows the stimulation period and is in the same direction as the preceding OKN Secondary and tertiary OKAN have been observed in monkeys (Buettner et al., 1976; Waespe and Henn, 1978a). These periodically reversing intervals of after nystagmus are beyond the scope of this report. They are also unaccounted for in models of optokinetic and vestibular nystagmus generation.

Organization of OKN, vestibular nystagmus and visual-vestibular interaction.

The results described above can be modelled mathematically by assuming that the visual and vestibular systems couple to the oculomotor system by separate direct pathways and by a common indirect pathway that contains the velocity storage mechanism (Cohen et al., 1977; Raphan et al., 1977, 1979). The term "direct" is not meant to imply a monosynaptic pathway but rather a quickly responding oligosynaptic pathway that goes around the velocity storage integrator to influence eye velocity. The direct visual pathways are similar to Robinson's fast optokinetic system (Robinson, 1975) and are responsible for the rapid changes in eye velocity at the beginning and end of OKN, and during fixation suppression (Raphan et al., 1979). The location of the direct visual oculomotor pathways is still largely unknown (see Henn et al., 1980 for a review). The direct vestibular pathway has been extensively studied (Lorente de No, 1933; Szentagothai, 1950; see Cohen, 1971, 1974 and Wilson and Melvill Jones, 1979 for review). It is composed of disynaptic and trisynaptic neuronal arcs that extend through the medial longitudinal fasciculus and across the floor of the brainstem to the eye muscle motoneurons. It is responsible for the rapid rise in eye velocity during steps of head velocity.

In contrast, the location of the storage mechanism or of the indirect pathways is at present largely unknown. Stored activity is most clearly seen during OKAN although it also contributes to the production of OKN and vestibular nystagmus. The central cancellation of after responses after rotation in light are other manifestations of stored velocity. The dynamic characteristics of the charge and discharge have been extensively studied for nystagmus and for visual-vestibular interactions in the horizontal plane (Cohen et al., 1977; Raphan et al., 1979), but little is known about velocity storage for nystagmus in the vertical plane.

Although the location of the velocity storage integrator is a matter of conjecture, results of Henn and co-workers indicate that neurons in the vestibular nuclei have firing rates that reflect stored activity related to slow phase eye velocity (Henn, Young and Finley, 1974; Waespe and Henn, 1977a,b, 1978b). Vestibular nuclei units respond to optokinetic stimulation by increasing their activity over 10 to 13 sec to a steady state frequency of firing that is maintained for as long as the stimulus lasts. Unit firing frequency declines during OKAN with approximately the same time course as slow phase velocity (Waespe and Henn, 1977a; Waespe, Henn and Miles, 1977). Firing frequency also mimicks slow phase velocities of horizontal vestibular nystagmus (Waespe et al., 1977) by increasing and decreasing over the same time course as the nystagmus. In the alert monkey, no vestibular nuclei neurons have the time constant of the activity coming from the peripheral end organ. All units that increase their firing rates during optokinetic stimuli in one direction also increase their firing rates during head rotation in the opposite direction (Waespe et al.,1977). This shows that visual information about surround movements is reflected in the vestibular nuclei. During visual-vestibular interaction, vestibular nuclei unit activity is more closely related to nystagmus slow phase velocity than to activity in the peripheral end organ. Units maintain a steady level of discharge when animals are given constant velocity rotations in light. When animals are rotated in darkness unit firing frequency falls over a much longer time course than the activity in the VIIIth nerve. During visual vestibular conflict stimulation, that is, when the animal and optokinetic drum are rotated together, nystagmus is generally suppressed, although unit activity is only partially attenuated. Firing rates during OKAN have a similar time course as the nystagmus but firing rates saturate at a lower velocity than peak OKAN slow phase velocities. Therefore, while it appears that units in the vestibular nuclei have access to stored activity related to slow phase velocity, it seems unlikely at present that the velocity storage integrator is in the vestibular nuclei.

Lesion data.

The close relationship between the velocity storage mechanism and the VOR is shown by lesions of the vestibular system. The peripheral apparatus must be preserved for velocity storage to be present, since destruction of the labyrinth not only abolishes vestibular nystagmus but permanently abolishes OKAN (Uemura and Cohen, 1972; Cohen, Uemura and Takemori, 1973; Collewijn, 1976; Zee, Yee and Robinson, 1976). In addition, OKN is impaired by labyrinthectomy. The maximum slow phase velocity of OKN in these animals is about 0.6 of normal, and is irregular. OKN and OKAN are unaffected if the canals are disabled by plugging, probably because the tonic activity of the vestibular nerve is preserved (unpublished observations).

Vestibular afferents project to the cerebellar flocculus, and flocculectomized animals have impaired OKN but OKAN is present (Takemori & Cohen, 1974). This suggests that the presence of the flocculus is not essential in order to charge the velocity storage integrator. Visual suppression of caloric nystagmus is severely impaired, however, after flocculus destruction (Takemori and Cohen, 1974). Lesions in nucleus prepositus disrupt OKN and cause a permanent loss of OKAN (Uemura and

Cohen, 1973, 1975); midline section of the medulla also causes OKAN to disappear (deJong, Cohen, Matsuo & Uemura, 1980). Thus velocity storage may be effected by neural groups in the region of the prepositus. This would be consistent with the finding that neural activity in the region of the prepositus is related to stimulus and to slow phase eye velocity (Blanks, Volkind, Precht and Baker, 1977), and receives visual and vestibular afferents (Baker and Berthoz, 1975; Gresty and Baker, 1976).

Anatomic substrate for horizontal and vertical gaze.

Different brain structures are involved in horizontal and vertical eye movements. The organization of structures responsible for horizontal eye movements has been extensively studied and has been recently reviewed (Raphan and Cohen, 1978; Bender, 1980). Briefly, neural activity in the rostral paramedian zone of the pontine reticular formation (PPRF) generates a burst or "pulse" of activity that initiates saccades and quick phases of nystagmus (Robinson, 1971). Direction, duration and amplitude of eye movement are coded in this phasic activity (Henn and Cohen, 1976). Activity in the caudal PPRF appears to have integrated the information from the PPRF burst neurons to produce a signal that is proportional to eye position and to slow phase velocity during ocular pursuit and slow phases of nystagmus (Keller, 1974). There are direct projections from the PPRF to ipsilateral abducens motoneurons in monkey (Buettner-Ennever and Henn, 1976). In addition, internuclear neurons in and around the abducens nucleus convey excitatory information to contralateral medial rectus motoneurons via the MLF (Baker & Highstein, 1975).

Structures involved in vertical gaze have been studied using lesion, stimulation and recording techniques, as well as clinical material and anatomical techniques (Smith, 1962; Pasik and Pasik, 1964; Pasik et al., 1969a,b; Pasik et al., 1971; Pasik and Pasik, 1972; Rosberg, Tos and Adser, 1972; Christoff, 1974; Buettner, Hepp and Henn, 1977; Buettner, Buettner-Ennever and Henn, 1977; Buettner-Ennever, 1977; Graybiel, 1977; Evinger et al., 1977; King and Fuchs, 1977, 1979; Buettner-Ennever and Buettner, 1978; Koempf et al., 1979; Steiger and Buettner-Ennever, 1979). The neuronal mechanisms that are involved in the control of vertical eye movements have been reviewed by Bender (1960, 1980). There appears to be a separation of mechanisms for upward and downward movements. Isolated bilateral lesions in the pretectum cause paralysis of upward gaze, and bilateral lesions in the mesencephalic reticular formation (MRF) in the vicinity of the red nucleus cause paralysis of downward gaze (Pasik et al., 1969; Koempf et al., 1979). Units in the latter region, variously referred to as the prerubral field, (Papez, 1942; Graybiel, 1977) or the rostral interstitial nucleus of the medial longitudinal fasciculus (rostral iMLF) (Buettner-Ennever, 1977), have activity that is related to parameters of vertical saccades. Amplitude, direction and change of position along a preferred plane of movement are coded by information contained in the burst of activity just prior to saccades (Buettner et al., 1977; King and Fuchs, 1977, 1979). Cells in the rostral iMLF receive afferents from the ipsilateral vestibular nuclei and PPRF, and project to the ipsilateral oculomotor nucleus. They probably form the immediate premotor structure for vertical saccades. As yet, the premotor signal for eye positions in the vertical plane and for pursuit eye movements have not been located.

Vertical OKN and the vertical VOR.

The asymmetry in vertical vestibular nystagmus and OKN has previously been described in terms of frequency or duration of nystagmus induced by step or sinusoidal velocity patterns. Vertical OKN was studied by Ohm (1922), Stiefel and Smith (1962), Collins et al. (1970), Collewijn and Noorduin (1972), Takahashi and Igarashi (1977), Takahashi et al. (1978), Dubois and Collewijn (1979a,b) and Erickson and Barmack (1980). In particular, Takahashi and Igarashi (1977) noted that there was little or no upward OKAN after upward OKN. Guedry and Benson (1970, 1971) reported that the gain of the vertical VOR in humans was symmetrical, but downward time constants were slightly longer. They noted that the frequency of downward nystagmus was 2 to 5 times higher than that of upward nystagmus. Horizontal nystagmus was reported to be longer lasting than vertical vestibular nystagmus (Melvill Jones, Barry and Kowalski, 1964; Benson and Bodin, 1966; Collins and Guedry, 1967; Guedry and Benson, 1970; Benson and Guedry, 1971). Visual-vestibular interaction in vertical nystagmus has been studied in relation to visual suppression of vertical nystagmus (Guedry, 1970; Guedry and Benson, 1970; Benson and Guedry, 1971; Guedry and Benson, 1971; Barnes, Benson and Prior, 1978). These investigators found that downward beating nystagmus induced by rotation in light was considerably more difficult to suppress visually than upward nystagmus was.

In summary, horizontal and vertical eye movement related regions in the brain are anatomically separate. Horizontal optokinetic and vestibular nystagmus have been extensively studied but less is known about vertical nystagmus. It would be instructive to determine if horizontal and vertical eye movements are functionally different. This work describes a striking asymmetry in velocity storage during vertical nystagmus. Every measure of stored velocity indicated that there was storage of activity related to slow phase eye velocity during downward nystagmus but little or no storage during upward nystagmus.

II. Methods.

Summary of techniques used.

Based on previous studies of horizontal nystagmus (Cohen et al., 1977; Raphan et al., 1979), several techniques were used to demonstrate and quantify stored activity related to slow phase eye velocity during vertical nystagmus. Peak velocities of OKAN and falling time constants of OKAN and vestibular nystagmus were calculated. Brief periods of optokinetic stimulation were given to reveal the charging time constant of stored velocity. The persistence of stored activity was examined by testing visual suppression of OKAN and vestibular nystagmus. Finally, the presence or absence of velocity storage and its contribution to the vertical VOR were tested by manipulating the relative velocity of the environment and the head during rotation. Nystagmus direction refers to the beating direction of the quick phase.

Subjects.

Five rhesus monkeys (Macaca mulatta), three cynomologous (Macaca fascicularis) and one nemestrina (Macaca nemestrina) were used in this study. They were juvenile females weighing 2.0 to 3.5 Kg. No consistent interspecies differences were observed, and their results are considered together. Not all monkeys were tested under every condition. Table 1 shows which monkeys were used in the tests described in this report. Monkeys were implanted under sodium pentobarbital (Nembutal)

TABLE 1

M#	Spc.	OKN	Freq.	OKAN TC	OKN Ch.	OKAN V.S.	VOR	VOR T.C.	VOR V.S.	VVI	Tilt
991	Rh.	H		H	H	H	H	H	H	V,H	
993	Rh.	H					V,H		V		
996	Rh.	V,H		V,H			V,H	V,H		V	
1101	Cy.	V,H	V,H	V			V,H	V	V	V,H	
1103	Cy.						H			H	
1111	Nem.				V	V					
1115	Rh.	V		V							
1118	Cy.			V	V					V	V
Z-P	Rh.	V					V				

V,H, vertical and horizontal trials
OKAN TC, VOR TC, time constants of OKAN and VOR
OKN Ch., OKN charge
OKAN V.S., VOR V.S., visual suppression of OKAN and vestibular nystagmus
VVI, visual-vestibular interaction

anesthesia with non-polarizing silver silver-chloride electrodes (Bond and Ho, 1970) and head restraint bolts. Electrodes were implanted in the zygomatic process at the lateral margin of each orbit and in the supra-orbital and infra-orbital ridge above and below each eye. The leads were passed subcutaneously to a connector embedded in an acrylic crown on the skull. Horizontal eye position was recorded using the two lateral electrodes. Vertical eye movements were measured by bridging the two supra-orbital and the two infra-orbital electrodes. This minimizes the effect of symmetrical off-vertical electrode placement (Young and Sheena, 1975). Figure 1 shows the placement of the electrodes and the manner in which they were connected to the amplifiers. When animals were not being tested the electrodes were shorted together. This reduces drift and offset.

Eye movement recording.

The electro-oculogram (EOG) was used to determine eye position. This technique makes use of the potential difference between the front and back of the eyeball (Mowrer, Ruch and Miller, 1936; Marg, 1951; Kris, 1958; Young, 1970; Young and Sheena, 1975). The origin of this potential is unclear although it is commonly referred to as the corneo-retinal potential. This term may be misleading since the potential returns in monkeys whose retinas and corneas are surgically removed (Pasik, Pasik and Bender, 1965). The EOG was amplified by a low drift, direct coupled amplifier with a fixed gain of 500 and a variable pass band. The pass band was usually set at D.C. to 75 Hz. The EOG was

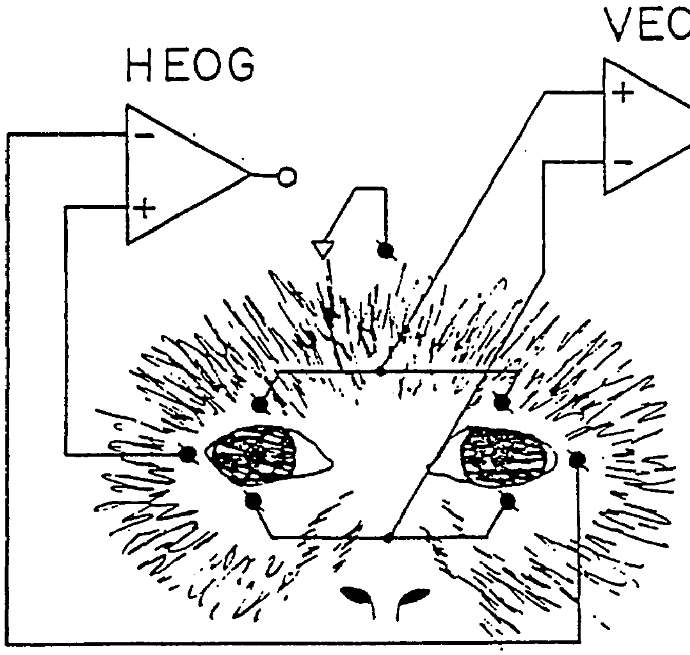


Figure 1. EOG recording. Each symbol represents an implanted silver silver-chloride electrode. The horizontal EOG was recorded between the two temporal electrodes and the vertical EOG was recorded between the top and bottom pairs of electrodes. The reference electrode was in the skull near the midline.

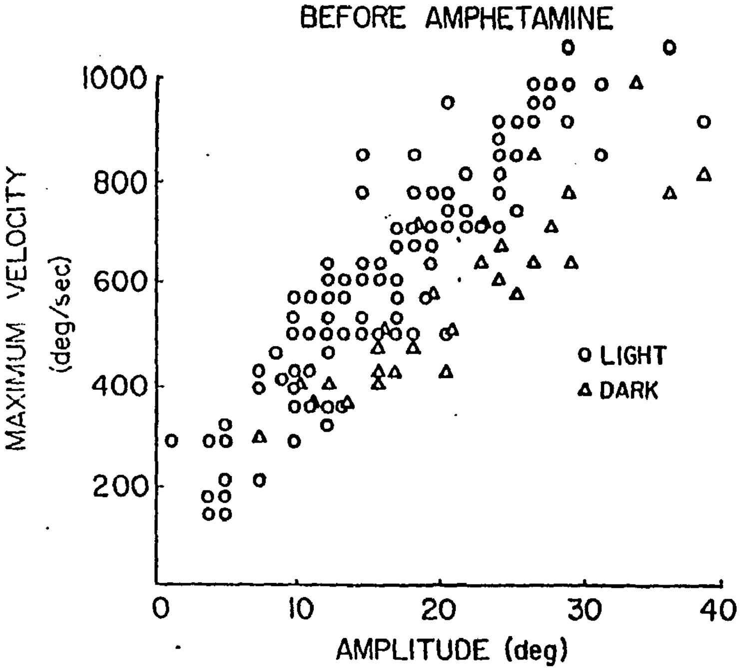
electronically differentiated using an amplifier with a time constant of 3 msec and the differential was rectified to get slow phase eye velocity. Horizontal and vertical EOG's, slow phase velocities, photocell signals and voltages representing drum or turntable position were written out on a Beckman Type R Dynograph and recorded on FM magnetic tape (Honeywell 7600). A small general purpose computer (DEC Lab 8/E) was programmed to plot the points of the graphs below.

Alertness.

An intramuscular dose of amphetamine sulfate (0.5 mg/Kg) was given 30 minutes prior to testing to maintain a constant level of alertness. Alertness maintains saccadic velocities along the "main sequence" of the saccadic amplitude-velocity relationship (Bahill, Clark and Stark, 1975; Bahill and Stark, 1975). Amphetamine sulfate does not markedly affect saccadic velocities nor amplitude-duration relationships (Cohen, Alpert, Komatsuzaki and Hyams, 1969; Komatsuzaki, Harris, Alpert and Cohen, 1969). Figure 2 shows that the amplitude-velocity relationship of quick phases of optokinetic nystagmus measured in one animal before and after administration of a small dose of amphetamine were similar. It was important that alterations in state of alertness not occur because they could cause variations in slow phase velocity that were unrelated to the experimental conditions. The effect of drowsiness on slow phase velocity is shown in Figure 3 recorded during vestibular nystagmus. Several times during this trial the animal became drowsy as shown by the absence of rapid eye movements. At these times its slow phase velocity

Figure 2. Effect of amphetamine on quick phase amplitude-velocity relatonship. A. Before amphetamine, the amplitude-velocity relationship is linear with a slope of about 35 deg/sec/deg. Quick phases in darkness had somewhat lower velocity. B. Thirty minutes after the administration of amphetamine, the slope of the data is approximately 30 deg/sec/deg. Quick phases in darkness are still somewhat slower than those in light, but not markedly so. These velocities are somewhat lower than saccadic velocities reported by Fuchs (1967).

A.


BEFORE AMPHETAMINE
MAXIMUM VELOCITY (deg/sec)
1000
800
600
400
200
0
10
20
30
40
AMPLITUDE (deg)
o LIGHT
Δ DARK

B.

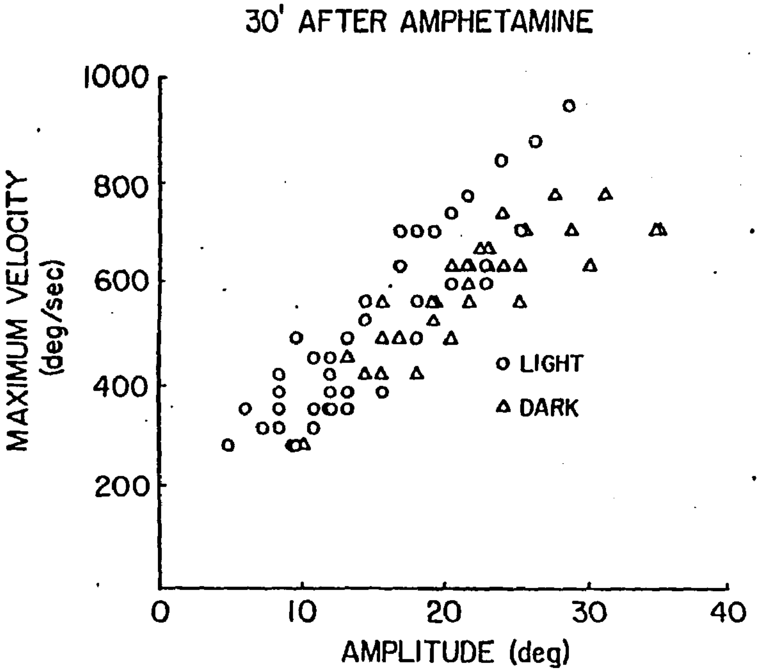
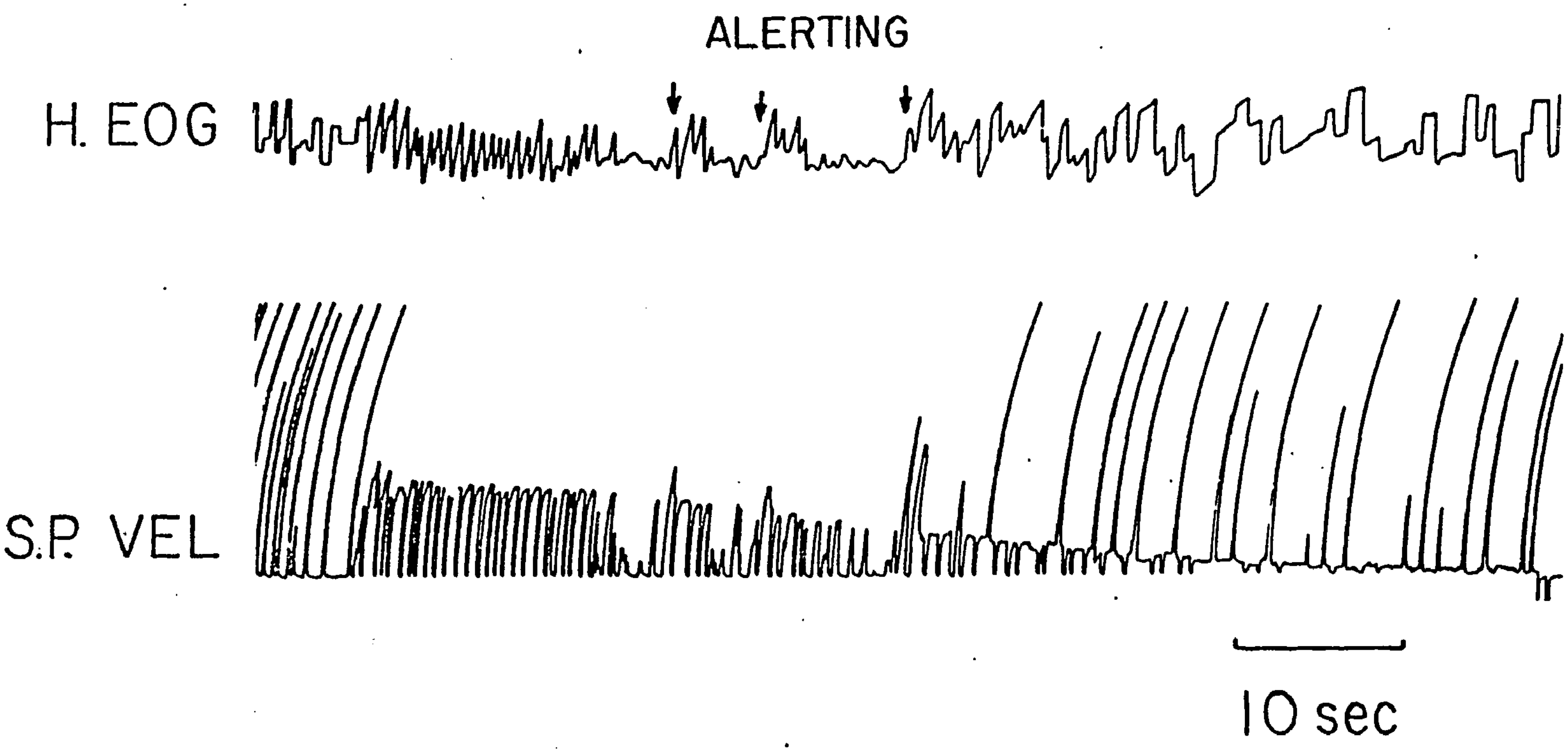

30' AFTER AMPHETAMINE
MAXIMUM VELOCITY (deg/sec)
1000
800
600
400
200
0
10
20
30
40
AMPLITUDE (deg)
o LIGHT
Δ DARK

Figure 3. Velocity profile of a sleepy monkey. Post rotatory response of a monkey after a velocity step of 60 deg/sec. Three times during this response the animal's eyes began moving slowly in association with drowsiness. Rapid and slow phase velocities during these episodes fell to zero. When the animal was alerted by shouting (arrows), nystagmus reappeared and slow phase velocity assumed its normal value.

VELOCITY PROFILE OF A DROWSY MONKEY



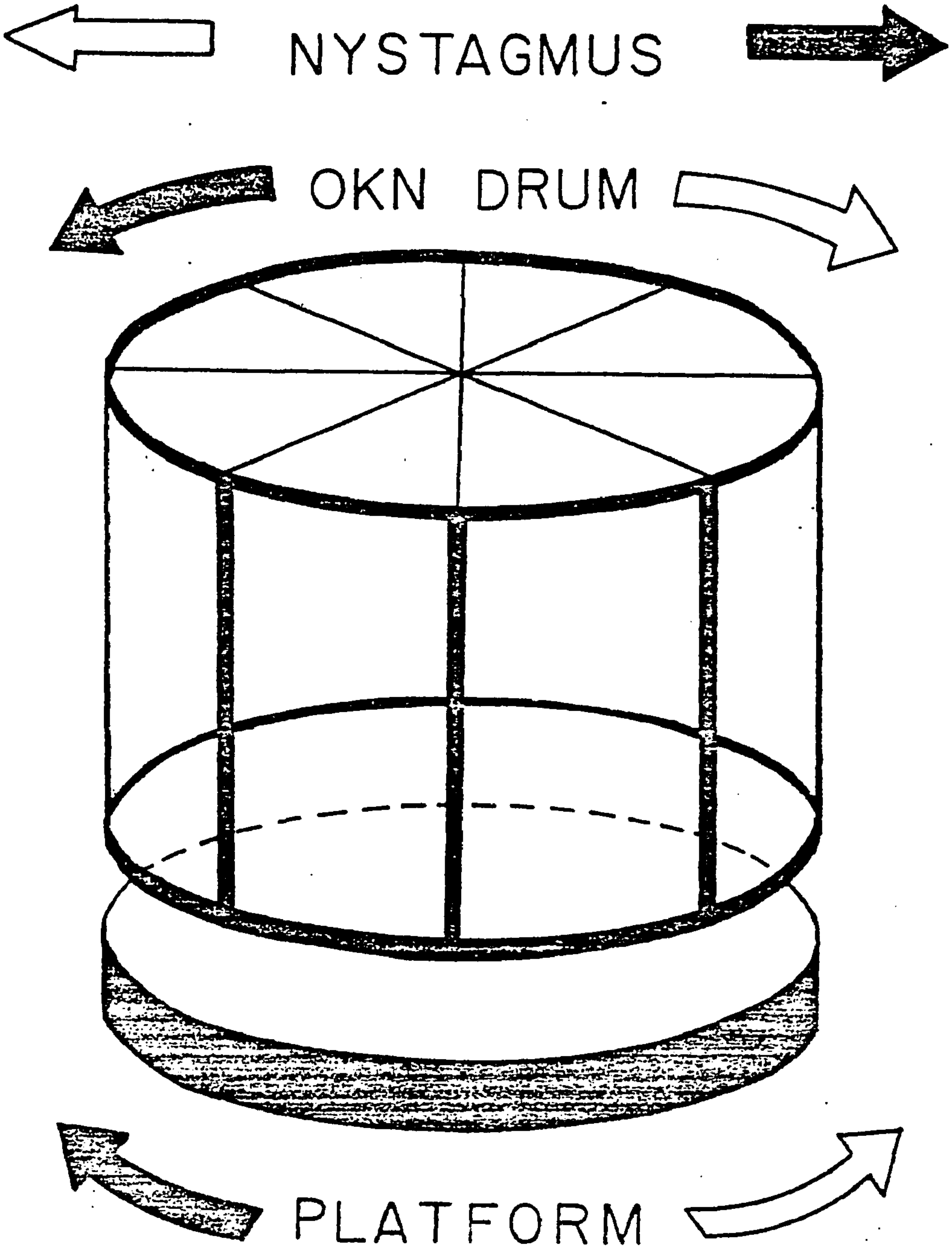
fell nearly to zero. When the animal was alerted by a sudden noise, eye velocity immediately returned to the expected level along the slow phase velocity envelope. This shows that central activity responsible for slow phase velocity was still present and declining over its own time course although eye movements had disappeared. Slow phase velocities of both vestibular nystagmus and OKN in alert animals were the same before and after amphetamine.

Optokinetic and vestibular stimulation.

A turntable (Industrial Controls) was placed under the center of an internally lit optokinetic drum (Industrial Controls) that surrounded the animal and filled its visual field. The turntable and drum are represented in Fig 4. The drum was 90 cm in diameter and 60 cm high. The drum walls were made of translucent white plastic and had 3 deg black stripes every 45 deg. A 75 watt enlarger bulb illuminated the inside of the drum at photopic levels. A mirror placed under the monkey's chin in the upright position and under the monkey's cheek when in the lateral position filled the visual field with moving contours during optokinetic stimulation. This resulted in full-field optokinetic stimulation which is most effective in evoking optokinetic nystagmus (Cohen et al., 1977).

Both drum and turntable were rim driven and servo controlled and could be independently driven in the same or opposite direction. Stimuli consisted of steps of velocity from 10 deg/sec to 180 deg/sec of platform rotation and up to 270 deg/sec of drum rotation. Platform

Figure 4. Optokinetic and vestibular stimuli. The drum and platform were oriented concentrically and could be rotated independently in the same or oposite direction and at the same or different velocities. Note that clockwise movement of the drum and counterclockwise movement of the platform both evoke nystagmus in the same direction. For vertical testing the monkeys were put in the lateral position with the interaural axis in the axis of rotation.


NYSTAGMUS
OKN DRUM
PLATFORM

accelerations were approximately 100 deg/sec/sec and decelerations were 120 deg/sec/sec. For velocity steps of 200 deg/sec or less, these values are sufficiently high to maximally excite the cupula (Goldberg and Fernandez, 1971). Vertical optokinetic nystagmus was induced in two ways. The animal was rotated in darkness in the left or right lateral position until the per rotatory nystagmus had subsided. Then the drum light was switched on to give a relative step of optokinetic velocity in the opposite direction. Secondly, the optokinetic drum was rotated around the animal while it was lying in the left or right lateral position. Then the drum light was switched on. These stimuli are theoretically equivalent and there were no obvious differences in the response to them. The first stimulus was used for most testing because slightly more of the visual field is filled during this stimulus. They are considered together in the Results section.

Since vertical vestibular nystagmus was induced by rotating the animal about an earth-vertical axis while lying on its side, the anterior and posterior semicircular canals, but not the otolith organs were dynamically activated. This creates a conflict between canal and otolith organ information since the canals signal that the head is moving in the vertical plane but there is no gravity related change in head position (Henn et al., 1980). However, vertical nystagmus induced with the animal on its side without a rotating gravity vector is analogous to horizontal nystagmus induced by rotation about a vertical axis with the animal upright (yaw motion). Thus the two can be compared using the same stimuli. Monkeys were also tested in an apparatus that has recently become available for full field vertical OKN in the upright position. Vertical OKN was not different, although vertical OKAN was affected. This is not the subject of this study but data from these experiments are shown at the end of the Results section.

Electro-oculography.

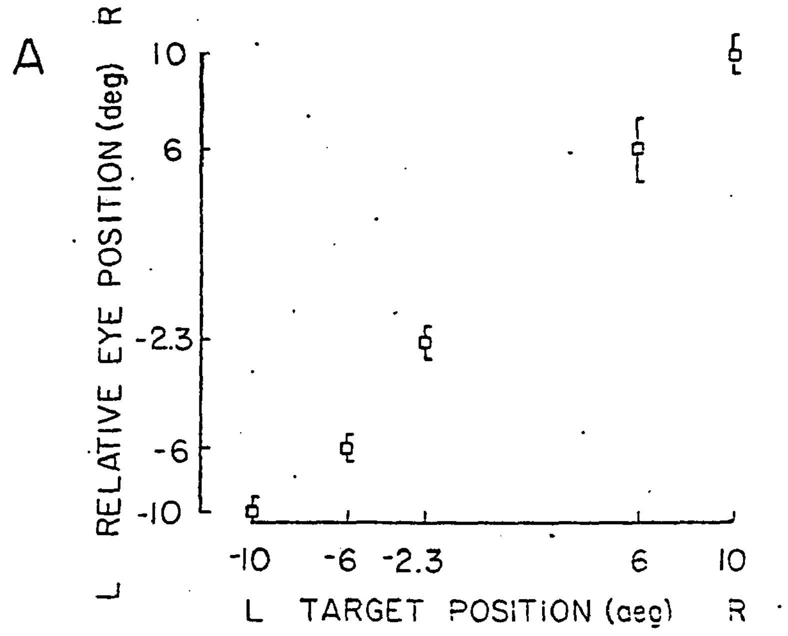
D.C. electro-oculography (EOG) was used to record eye position because it is simple, reliable and does not interfere with vision or eye motility. With silver silver-chloride electrodes, drift was minimal over the testing session of 3 hours. The eye position signal was accurate to + or - 0.5 to 1.0 deg and was linear over a 30 deg range. The sensitivity of this technique is lower in humans when surface electrodes are used, being + or - 1.5 to 2.0 deg due to a lower signal to noise ratio (Young and Sheena, 1975). Figure 5 shows eye positions of a monkey that was trained to look at spots of light on a TV screen for a water reward. The Wurtz (1969) paradigm was used. The computer was programmed to present the spot at points on the screen in a quasi-random order. Both horizontal and vertical EOG's varied linearly with target position over the range of target presentations, which was about + and - 10 deg. This provides evidence that the differences observed between upward and downward nystagmus that will be described were not due to nonlinearities in the vertical EOG.

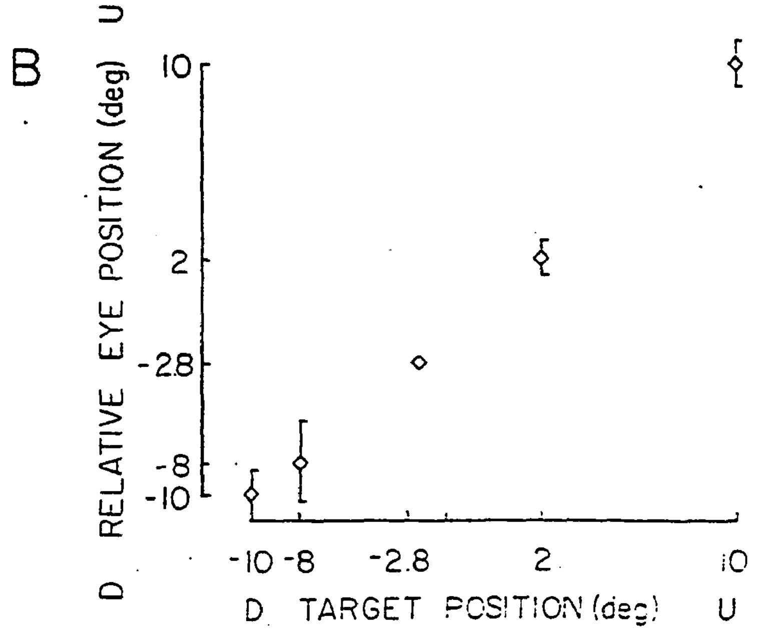
In light there are few changes in the gain of the EOG over time.

EOG gain = change in eye position / change in EOG voltage.

However, if the animal is put in darkness the standing corneo-fundal potential varies (Miles, 1940; Kris, 1958; Arden and Kelsey, 1962;

Figure 5. EOG linearity. These are averaged EOG potentials of eye movements in the horizontal (A) and vertical (B) direction. Each symbol represents the mean of 3 to 12 fixations. The animal was trained to fixate spots of light that appeared on a TV screen. Although the gains of the horizontal and vertical EOG's were different, each was linear over a twenty degree range. This shows that the asymmetries in gain in vertical nystagmus reported below are not due to asymmetries in the vertical EOG.


A
L RELATIVE EYE POSITION (deg) R
10
6
-2.3
-6
-10
-10
-6
-2.3
6
10
L TARGET POSITION (deg) R


B
D RELATIVE EYE POSITION (deg) U
10
2
-2.8
-8
-10
-10
-8
-2.8
2
10
D TARGET POSITION (deg) U

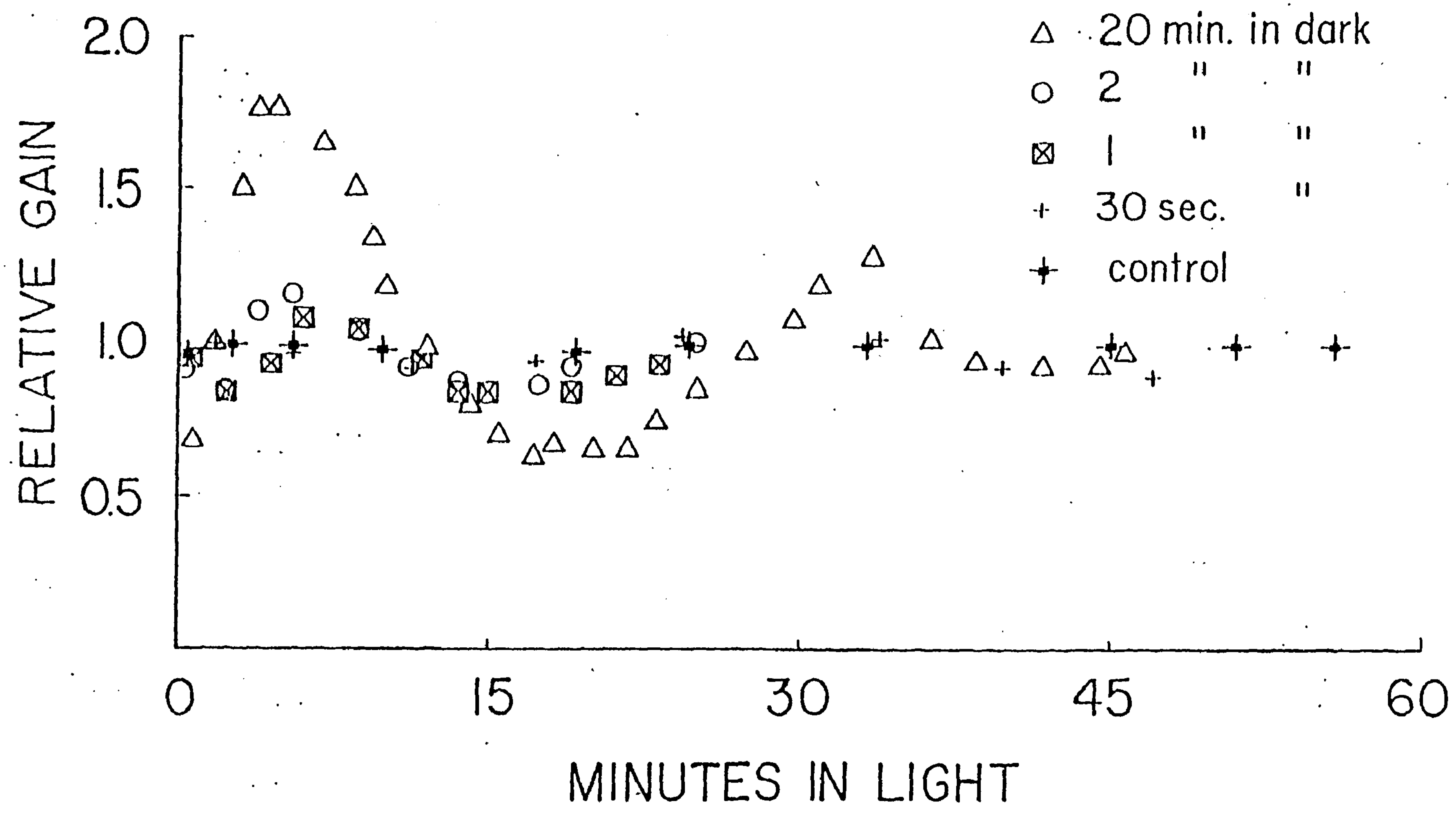
Horsten, Philipszoon and Winkelman, 1963; Gonshor and Malcolm, 1971). The result is that a given change in eye position results in a different EOG voltage change. The gain change can amount to + or - 50%. Figure 6 shows the results of an experiment that was performed to test EOG variability as a function of time in darkness. The response to a period in darkness was a damped oscillation in EOG gain with peak to peak amplitude decreasing over time. After 20 minutes of dark adaptation the EOG gain changed by at least + or - 50% in the hour over which it was measured. This graph closely resembles the curves published by Kris (1958), (Figure 7), and Arden and Kelsey (1962). Shorter periods of dark adaptation resulted in lesser peak to peak changes in gain, and with 30 sec or less exposure to dark, EOG gain was unaffected. Based on these data, observation times of per and post rotatory nystagmus and OKAN in darkness were limited to approximately 30 to 45 seconds.

During blinks, the vertical EOG is contaminated by an artifact that is most likely caused by movement of the upper eyelid (Ford, 1959; Melvill Jones and Barry, 1965). There is a sharp positive-negative deflection in the EOG due to the upper lid moving rapidly down and then up. Eye position is obscured during blinks. Portions of the EOG record and slow phase velocity trace that contained blink artifacts were not measured.

Calibrating slow phase velocities; normalizing responses.

Since the gain of the EOG can vary, it was calibrated by rotating the animal in light at 20 deg/sec before each trial. This condition

Figure 6. Change in EOG gain after varying periods of preceding darkness. A monkey was in darkness for the period of time indicated by the symbols. It was then given 45 deg/sec optokinetic stimulation, and the steady state level of OKN slow phase velocity was measured for up to 45 minutes afterwards. Changes in gain resembled a damped oscillation that decreased over 75 sec. The amount of change increased with increasing periods of dark adaptation. Note that when changes in light level are avoided (control) EOG gain changes are minimal.



RELATIVE GAIN
2.0
1.5
1.0
0.5
0
15
30
45
60
MINUTES IN LIGHT
△ 20 min. in dark
○ 2 " "
⊠ 1 " "
+ 30 sec. "
✚ control

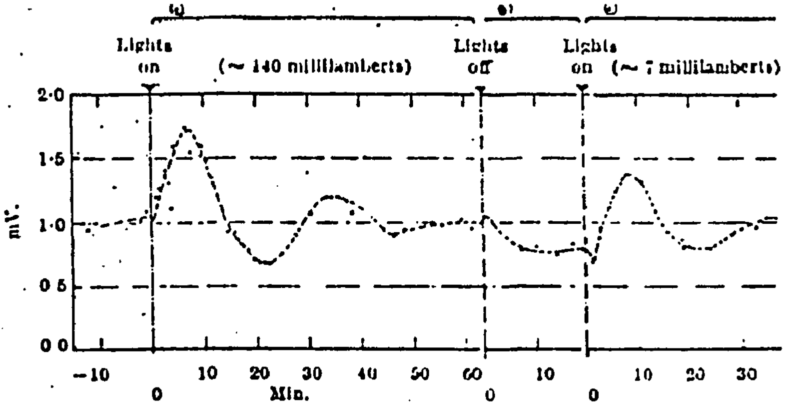


Fig. 2. Changes in eye potential-level during adaptation successively to *(a)* strong illumination; *(b)* darkness; *(c)* moderate illumination. Subject: *RS.* Ordinates: change in potential across electrode-pair lateral and mesial to left eye, produced by standard 60° horizontal fixation shifts

Figure 7. Changes in the corneofundal potential during changes in illumination. From Kris (1958). This trace shows the similarity of changes in the corneofundal potential after 10 or more minutes of dark adaptation and the changes in EOG gain in Figure 6.

combines optokinetic and vestibular stimulation and constitutes a maximal drive on the oculomotor system. A large body of evidence indicates that the gain of the vestibulo-ocular reflex (VOR) is unity in light for velocity steps of 20 to 60 deg/sec in primates, including humans (Melvill Jones, 1966; Meiry, 1971; Robinson, 1976; Barr, Schultheis and Robinson, 1976; Keller, 1978; Waespe, Henn and Isoviita, 1980). Regardless, all experimental values are expressed relative to this calibrating slow phase velocity and are called normalized slow phase velocity.

Experimental methods; measurement of time constants.

Time constants of decline, rather than duration of nystagmus were used to describe the persistence of stored activity during OKAN and vestibular nystagmus. They can be readily applied to models of the oculomotor and vestibular systems. Time constants were determined using a technique developed by Raphan (Cohen et al., 1977). The area under the slow phase velocity profile was measured with a digital planimeter (Numonics) to get total slow phase eye deviation. This value was divided by the peak value of the response. Time constants of rising functions, viz., "charge" characteristics of OKN and OKAN, were estimated in a similar way except that the steady state velocity was taken as the asymptote. The mathematical derivation of this technique is given in Cohen et al., (1977).

Time constants of OKAN and vestibular nystagmus decrease with repeated testing (Cohen et al., 1977) and longer durations of optokinetic stimulation (Buettner et al., 1976). Most animals used in this study were tested when they were at an intermediate level of adaptation. However, one animal (M 991) had been extensively tested. This animal had the shortest time constants of decline of OKAN and vestibular nystagmus.

Charge characteristics of OKN and OKAN.

Brief periods of optokinetic stimulation were given to test the dynamic characteristics of OKN and OKAN in the time domain. The technique is similar to that used to study horizontal OKN and OKAN (Cohen et al., 1977). From these data it was also possible to infer how activity responsible for OKAN increased during the period of stimulation. This was done by rotating the drum in darkness and pulsing on the light with a digital timer to give variable durations of optokinetic stimulation. OKAN was recorded in darkness. Peak velocities of OKN and OKAN were measured and normalized relative to a calibration response.

Visual suppression.

Brief periods of vision during OKAN and post rotatory nystagmus were given to determine how they affected activity responsible for inducing nystagmus. This is similar to the technique described originally in our study of horizontal OKN and OKAN (Cohen et al., 1977). OKN and OKAN were induced by 40 seconds of stimulation. Three to five seconds after OKAN had begun, when the drum was stationary, a 75 watt incandescent enlarger bulb was turned on for periods from 100 msec to 30 sec using either a digital photographic timer (EPOI) or a triac circuit that was gated by digital timing modules (WPI). The rising time constant of the light was 20 msec and the falling time constant was 40 msec. This illuminated the drum for a variable interval before turning the light off again. Peak slow phase velocities of OKAN or vestibular nystagmus just prior to the interval, and the peak "recovery" slow phase velocity just after the interval, were measured. The result was expressed as a ratio of "recovery" velocity divided by the pre-suppression slow phase velocity.

Data measurement.

Pen deflections representing slow phase eye velocities and stimulus variables were measured with calipers. Noise in the differentiated EOG was reduced using a low pass filter (-3 dB at 22 Hz). At the gain settings used in these experiments the peak to peak noise on the slow phase velocity trace was between 5 and 10% of the slow phase velocity. The error of measurement was greatest at low velocities.

Mean maximum slow phase velocity was used as the index of slow phase velocity. This measurement was an estimated value taken from a portion of the record where the slow phase velocity was stable. Repeated measurements of the same data yielded similar results. The data were entered into files on DECtapes for later analysis by computer.

III. Results.

Vertical OKN.

Typical examples of downward nystagmus in one animal (M 1101) are shown in Figure 8. At the onset of stimulation there was a quick rise in slow phase velocity to a value that was close to the maximum velocity for the trial. For stimulus velocities below 50 to 60 deg/sec, eye velocity was maintained at that level for the duration of stimulation. Above 60 deg/sec there was a slow rise to a steady state level. Slow phase velocities were well maintained up to 80 deg/sec. Above that they became increasingly irregular.

Horizontal OKN of another monkey is shown in Fig. 9 for comparison. There was a prominent rapid and slow rise in eye velocity and eye velocities were well maintained up to 150 deg/sec. Otherwise, it was similar to downward nystagmus. In contrast upward OKN was much weaker and more irregular than either downward or horizontal OKN (Fig. 10). Slow phase velocities were maintained only up to 20 deg/sec and above 40 deg/sec were very irregular. There was no slow rise in slow phase velocity after the initial rapid rise during upward OKN.

Peak slow phase velocity of OKN was measured and normalized relative to a 20 deg/sec calibration response. Ten consecutive beats of nystagmus were measured at a section of the record where it appeared that the animal had reached the steady state velocity, or where the record appeared stable. Slow phase velocities for downward OKN in the animal whose records are shown in Figures 8 and 10 increased linearly

Figure 8. Downward OKN and OKAN. The top two traces are vertical eye position and slow phase velocity, respectively, of OKN and OKAN at 20 deg/sec. The other traces are rectified eye velocity traces showing slow phase velocity. The numbers to the left of the traces refer to the stimulus velocity in deg/sec. At the downward arrow the drum light was turned out and downward OKAN was recorded for 20 to 60 sec. Note that above 80 deg/sec variability in slow phase velocity increased, and that in this monkey the response was poor at 180 deg/sec.

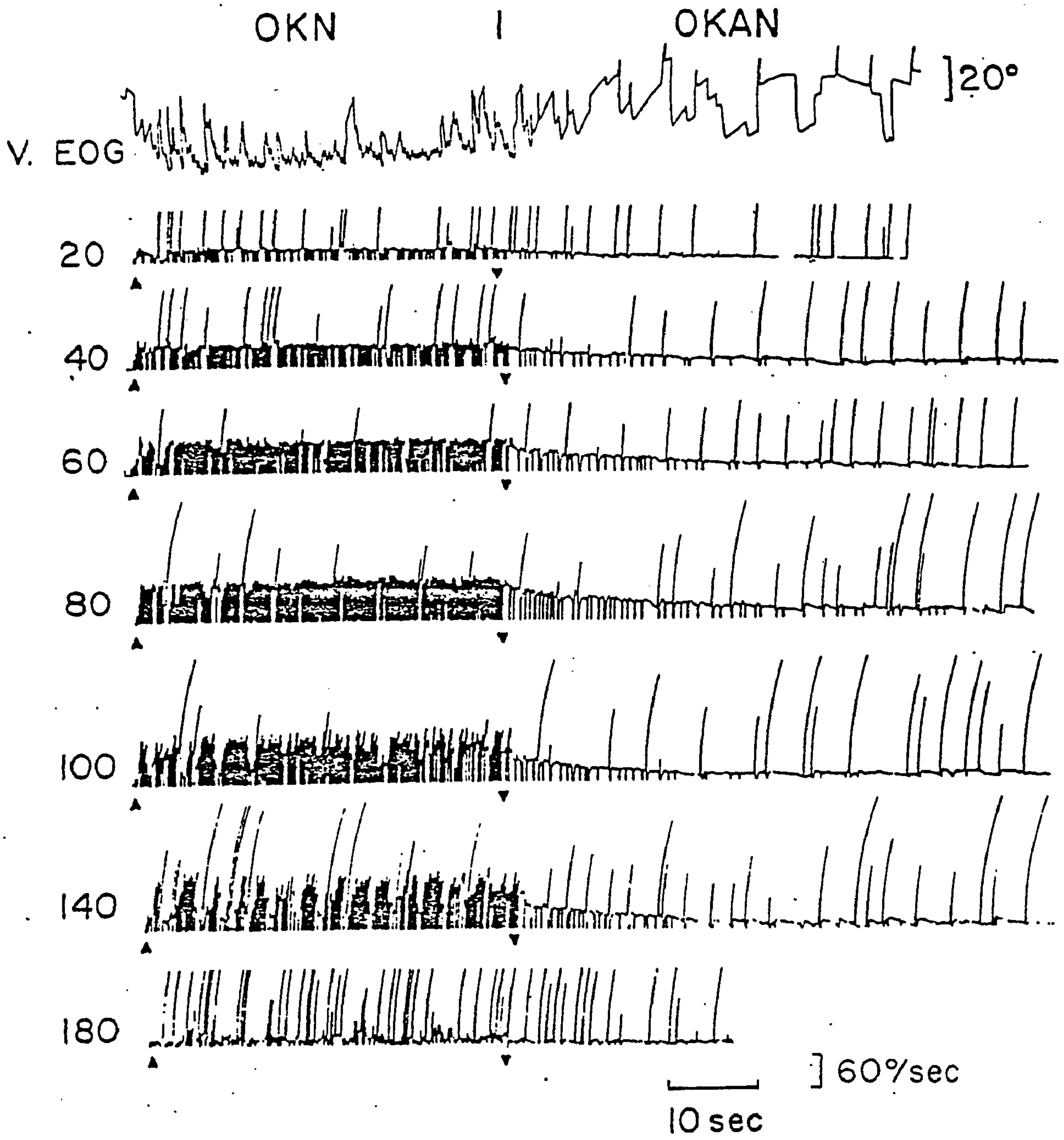

OKN
OKAN
V. EOG
]20°
20
40
60
80
100
140
180
] 60°/sec
10 sec

Figure 9. Horizontal OKN and OKAN. The top trace is horizontal eye position. The remaining traces are the slow phase velocities of OKN and OKAN. The numbers to the right of the traces indicate the stimulus velocity in deg/sec.

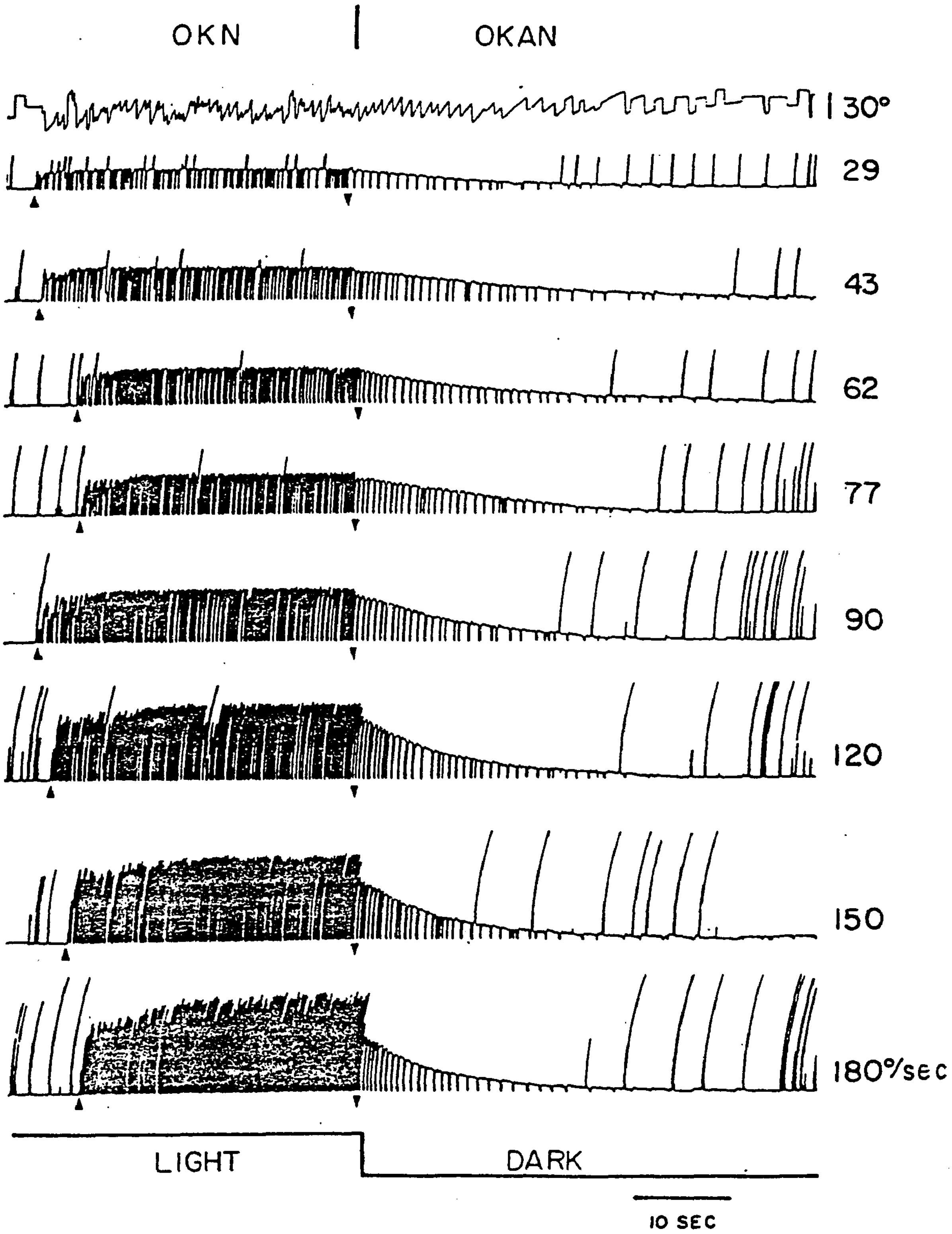

OKN
OKAN
30°
29
43
62
77
90
120
150
180°/SEC
LIGHT
DARK
10 SEC

Figure 10. Upward OKN and OKAN. The top trace is vertical eye position. The traces below are slow phase velocities of upward OKN and OKAN. The numbers to the left of the traces refer to the stimulus velocity in deg/sec. Note that upward OKN was irregular and that upward OKAN was weak or absent. The sharp deflections in the slow phase velocity traces represent the high velocity of forward saccades and blinks.

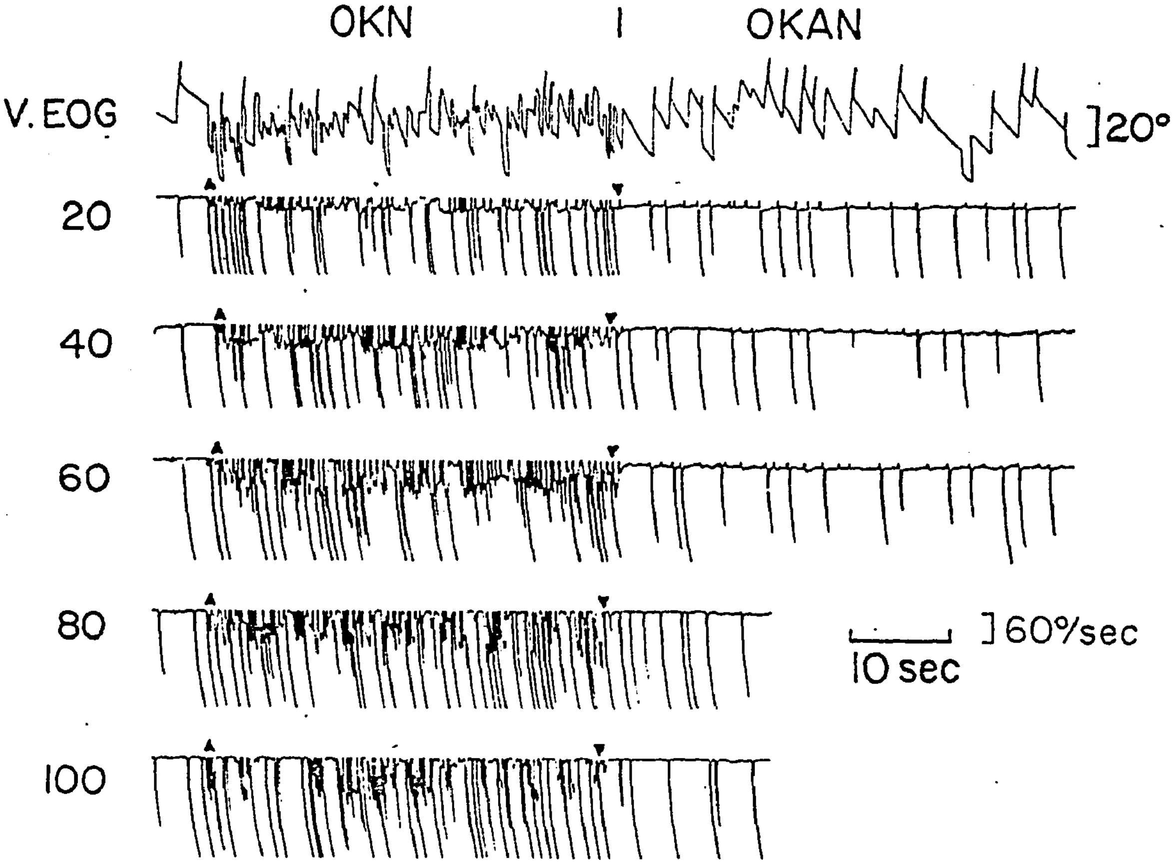
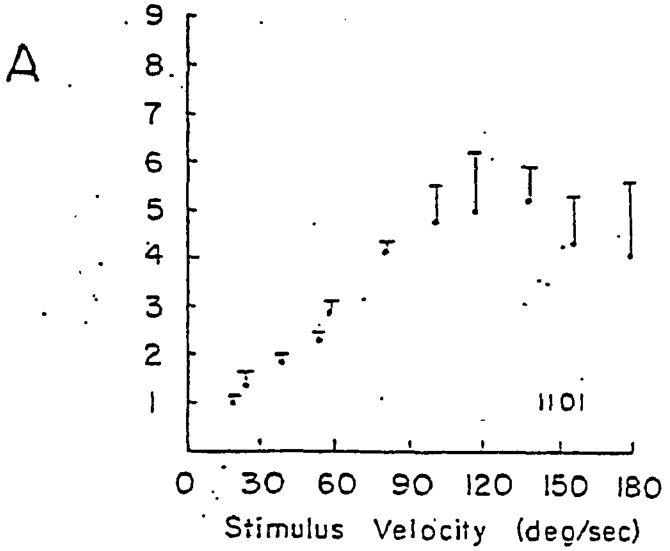
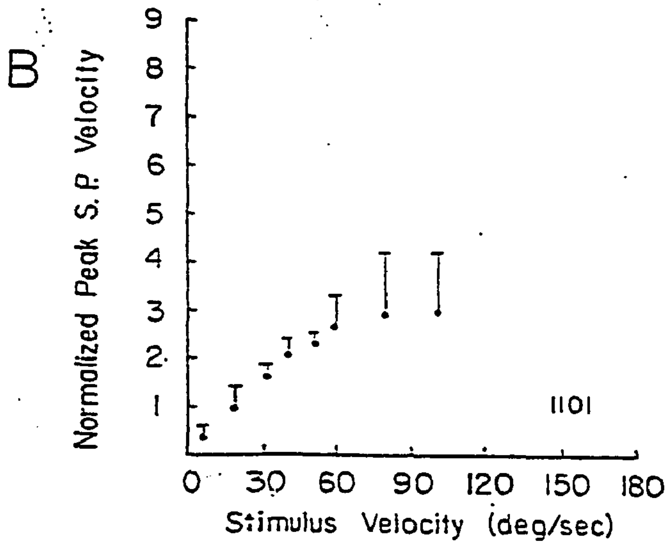
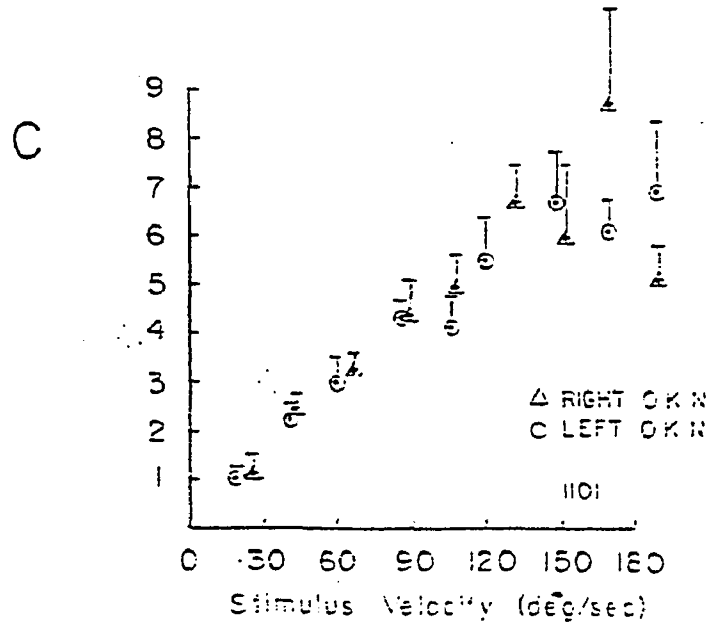

OKN
OKAN
V. EOG
]20°
20
40
60
80
100
]60°/sec
10 sec

Figure 11. Individual data from M 1101. These data are normalized peak slow phase velocities from experiments similar to those in Figures 8-10. The points are mean values and the bars represent one standard deviation. They were calculated from 10 consecutive beats in three periods of OKN. Note that variability increases above 90 deg/sec for downward OKN (A) and above 60 deg/sec for upward OKN (B). Horizontal data are presented in (C). Note that the gain of horizontal OKN was higher than that of vertical nystagmus, and that left and right OKN were symmetrical.


A
9
8
7
6
5
4
3
2
1
1101
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)


B
Normalized Peak S.P. Velocity
9
8
7
6
5
4
3
2
1
1101
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)


C
9
8
7
6
5
4
3
2
1
△ RIGHT OKN
○ LEFT OKN
1101
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)

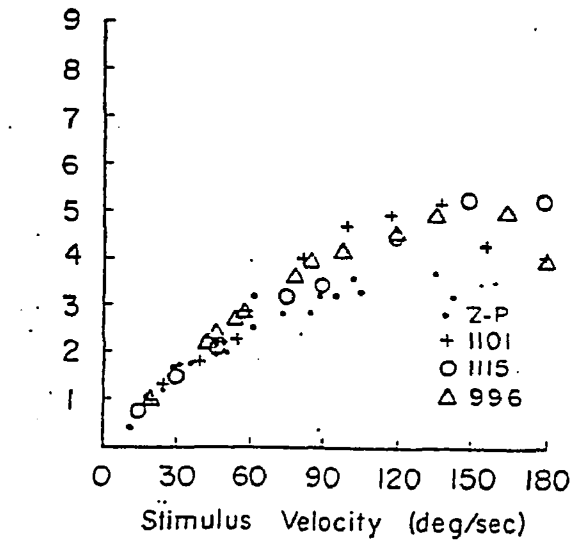
with a gain of about 1.0 for stimulus velocities to 90 deg/sec (Fig. 11A). Slow phase velocity continued to increase at a sharply lower gain for stimuli up to 140 deg/sec and then fell at higher stimulus velocities. There was a "soft" saturation level of 90 to 100 deg/sec. That is, slow phase eye velocities did not reliably exceed 100 deg/sec even though stimulus velocities increased to 180 deg/sec. Thus the limit of unitary gain of optokinetic following with upward slow phases and downward quick phases in this animal was around 80 to 90 deg/sec, although the eyes could momentarily attain higher slow phase velocities for faster stimuli. By contrast, slow phase velocities of upward OKN were more irregular and did not compensate well for velocity steps of full field stimulation above 40-50 deg/sec (Fig. 11B). They saturated at about 60 deg/sec. Both upward and downward OKN velocities were less than horizontal velocities that increased with unity gain to about 130 to 170 deg/sec (Fig. 11C).

OKN Group Data.

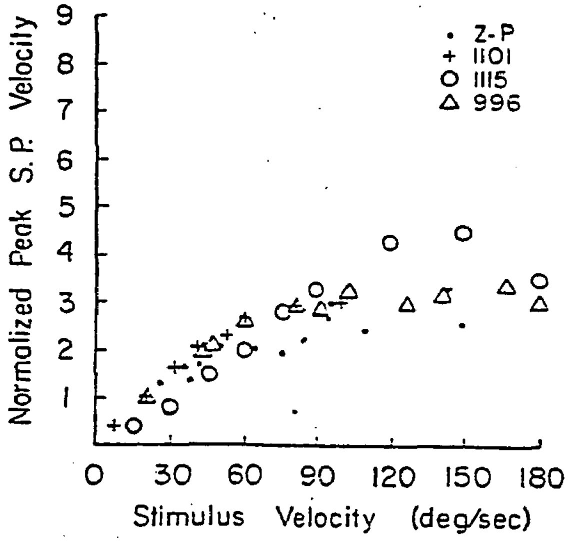
Normalized steady state velocities of M 1101 and three other monkeys (Z-P, 996, 1115) were plotted against stimulus velocity in Figures 12 and 13. The group data conform to the individual data shown in Fig. 11. For downward nystagmus slow phase velocities increased linearly with increases in stimulus velocity to 60 deg/sec with a gain of 0.90 to 0.96 (Fig. 12A, 13A). Above 70 deg/sec slow phase velocity continued to increase up to a saturation velocity of 80 and 100 deg/sec. This saturation level is somewhat higher than that obtained by Takahashi

Figure 12. Vertical and horizontal OKN, group data. Downward (A), upward (B) and horizontal (C) normalized OKN slow phase velocities are plotted versus stimulus velocity. Each symbol represents the data from one monkey. Note that the scatter of data is least below 60 deg/sec.

A


9
8
7
6
5
4
3
2
1
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)
• Z-P
+ 1101
O 1115
Δ 996

B


Normalized Peak S.P. Velocity
9
8
7
6
5
4
3
2
1
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)
• Z-P
+ 1101
O 1115
Δ 996

C

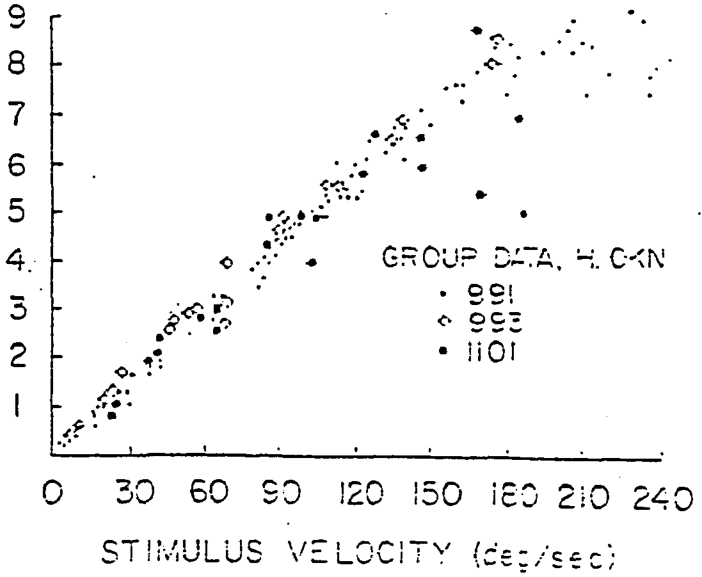
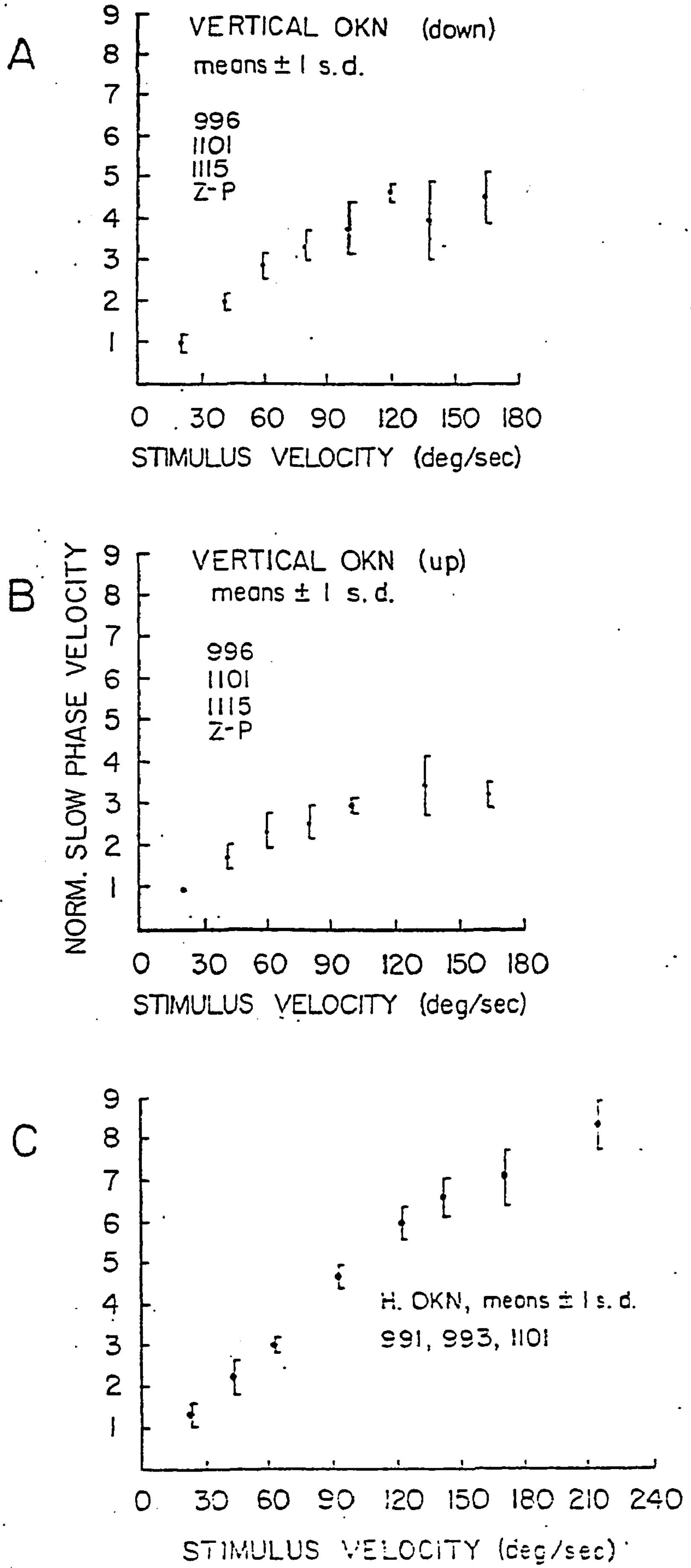

9
8
7
6
5
4
3
2
1
0
30
60
90
120
150
180
210
240
STIMULUS VELOCITY (deg/sec)
GROUP DATA, H. OKN
• 991
◇ 993
• 1101

Figure 13. Vertical and horizontal OKN, group means and standard deviations. Means and standard deviations were calculated from the data of Figure 12 and plotted as a function of stimulus velocity for downward (A), upward (B) and horizontal (C) OKN.

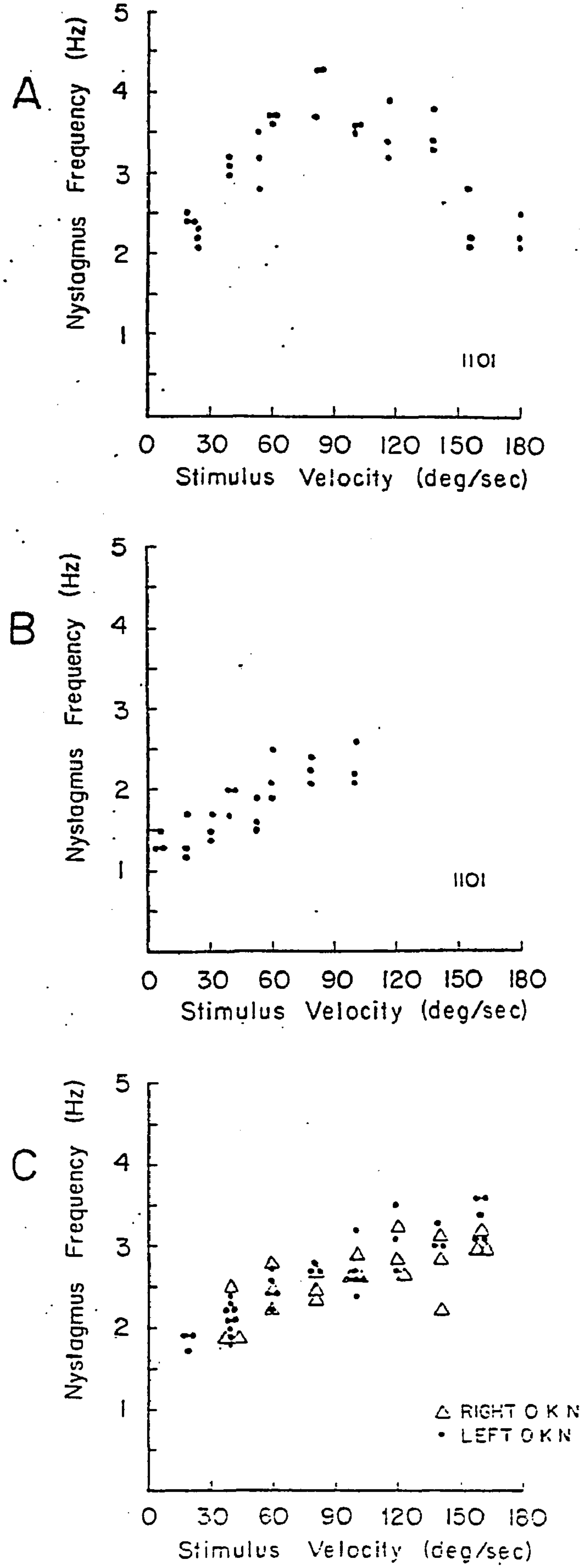

A
VERTICAL OKN (down)
means ± 1 s.d.
996
1101
1115
Z-P
9
8
7
6
5
4
3
2
1
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)
B
NORM. SLOW PHASE VELOCITY
VERTICAL OKN (up)
means ± 1 s.d.
996
1101
1115
Z-P
9
8
7
6
5
4
3
2
1
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)
C
H. OKN, means ± 1 s.d.
991, 993, 1101
9
8
7
6
5
4
3
2
1
0
30
60
90
120
150
180
210
240
STIMULUS VELOCITY (deg/sec)

and Igarashi (1977). For upward nystagmus (Fig. 12B, 13B) mean slow phase velocity had a unity gain only up to 20 deg/sec. Above this slow phase eye velocity increased with stimulus velocity at a lower gain to about 60 deg/sec with some individual variation. In contrast, horizontal OKN slow phase velocities reached higher levels increasing with a gain close to unity up to 120 deg/sec, saturating between 140 and 160 deg/sec (Fig. 12C, 13C). Individual animals were capable of reaching levels as high as 180 deg/sec during horizontal OKN.

Frequency of vertical OKN.

Beat frequencies of nystagmus were measured over 10 second periods. Frequency increased with increases in stimulus velocity. Generally values for downward nystagmus were higher than those for either upward or horizontal nystagmus. Fig. 14 is taken from data similar to those shown in Figs. 8-10. The beat frequency of upward nystagmus varied from about 1.3 Hz at 10 deg/sec to 2.3 Hz at 100 deg/sec (Fig. 14B) whereas the frequency of downward nystagmus varied from 2.3 Hz at 20 deg/sec to 4.2 Hz at 80 deg/sec (Fig. 14A). Peak beat frequency of downward OKN occurred at the highest velocity that had low variability of slow phase velocity. In comparison, beat frequencies of horizontal OKN were about 1.8 Hz at 20 deg/sec and increased steadily to a maximum frequency of about 3.3 Hz at 160 deg/sec (Fig. 14C). Thus the asymmetry in vertical OKN was reflected in its frequency as well as in slow phase velocity.

Figure 14. Frequency of nystagmus. A. Beat frequencies of downward nystagmus plotted versus drum velocity. The function is an inverted U with a peak of about 4 beats/sec at around 80 deg/sec. B. Beat frequencies of upward nystagmus are plotted against stimulus velocity. Frequencies of upward OKN were always lower than those of downward OKN at the same stimulus velocity. C. Horizontal nystagmus frequency for comparison. It ranged from 2 to 3.5 beats/sec, increasing with stimulus velocity. Note that there was no difference in frequency of left or right nystagmus. These nystagmus frequencies fell between values for downward and upward nystagmus frequency, up to 90 deg/sec.


A
Nystagmus Frequency (Hz)
5
4
3
2
1
1101
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)
B
Nystagmus Frequency (Hz)
5
4
3
2
1
1101
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)
C
Nystagmus Frequency (Hz)
5
4
3
2
1
△ RIGHT O K N
• LEFT O K N
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)

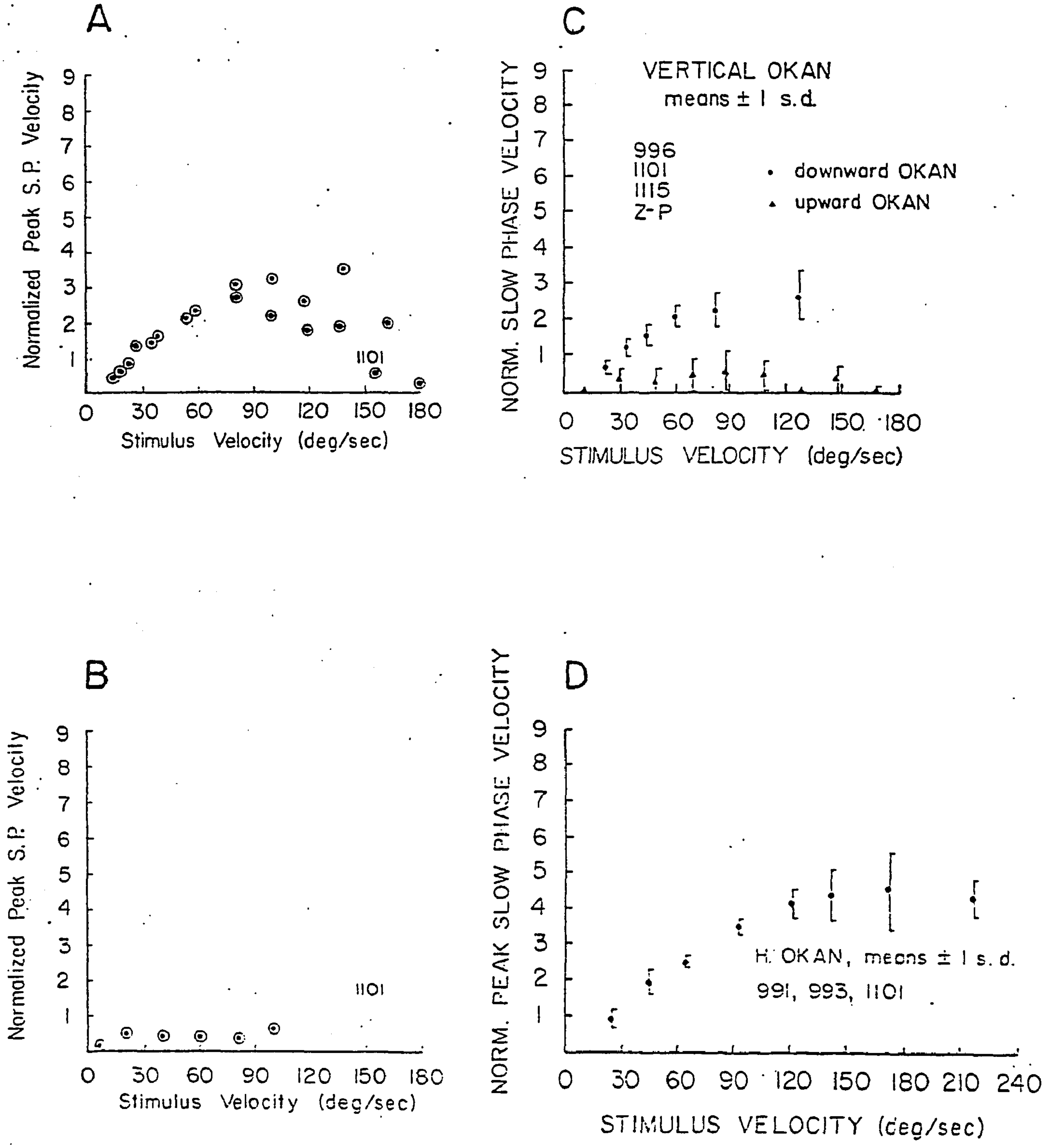
Vertical OKAN.

If an animal is put in darkness after optokinetic nystagmus, the eyes continue to beat with decreasing velocity for a variable period of time (Figures 8-10). This after response is referred to as optokinetic after nystagmus (OKAN) (Ohm 1922, 1927; Ter Braak 1936; Krieger and Bender, 1956). During downward OKAN following stimulation at 60 deg/sec or less, slow phase velocity initially fell to 0.85 to 0.75 of the steady state OKN velocity. After the rapid drop there was a gradual, approximately exponential, decline of slow phase velocity over 30 to 60 sec. The peak value of OKAN was used as a measure of the amount of activity that had been stored during OKN; the time constant of decline of slow phase velocity was used to characterize the time course over which this stored activity was dissipated (Cohen et al., 1977).

In monkey 1101 peak downward OKAN slow phase velocity increased with stimulus velocity with a gain of about 0.75 to about 60 deg/sec (Fig. 15A). Thus, OKAN slow phase velocity saturated at about 45 deg/sec even though downward OKN could reach higher levels. This saturation level was the point above which optokinetic slow phase velocities became increasingly variable. This is consistent with the interpretation that one effect of stored activity is to smooth and regularize the slow phase velocity of OKN (Cohen et al., 1977). Horizontal OKAN in this animal saturated at about 70 deg/sec.

Unlike downward or horizontal OKAN, upward OKAN was either weak or absent regardless of stimulus velocity or OKN slow phase velocity (Fig. 10, 15B). When it occurred, upward OKAN had similar durations as

Figure 15. Vertical and horizontal OKAN. A and B show normalized peak slow phase velocities of downward and upward OKAN, respectively, in M 1101. Peak velocities of downward OKAN increased following stimulation up to 80 deg/sec. Upward OKAN was weak. C shows means and standard deviations of downward (circles) and upward (triangles) OKAN of 1101 and three other monkeys. Note that the group data are similar to the individual data. D shows horizontal OKAN group means and standard deviations for comparison. Note that horizontal OKAN was more vigorous than downward OKAN and saturated at a higher velocity.


A
Normalized Peak S.P. Velocity
9
8
7
6
5
4
3
2
1
1101
0
30
60
90
120
150
180
Stimulus Velocity (deg/sec)
C
NORM. SLOW PHASE VELOCITY
VERTICAL OKAN
means ± 1 s.d.
996
1101
1115
Z-P
• downward OKAN
▲ upward OKAN
STIMULUS VELOCITY (deg/sec)
B
Normalized Peak S.P. Velocity
1101
Stimulus Velocity (deg/sec)
D
NORM. PEAK SLOW PHASE VELOCITY
H. OKAN, means ± 1 s.d.
991, 993, 1101
210
240
STIMULUS VELOCITY (deg/sec)

downward or horizontal OKAN (compare OKAN after 20 deg/sec stimulation in Fig. 8 and 10). This suggests that activity responsible for upward OKAN was lost over a similar time course as that for downward or horizontal OKAN. Group data from three other animals are presented in Fig. 15C. They were the same as the individual data in Fig. 15 A,B. Group data of horizontal OKAN are presented for comparison in Fig. 15D. Horizontal OKAN reached higher velocities than downward OKAN.

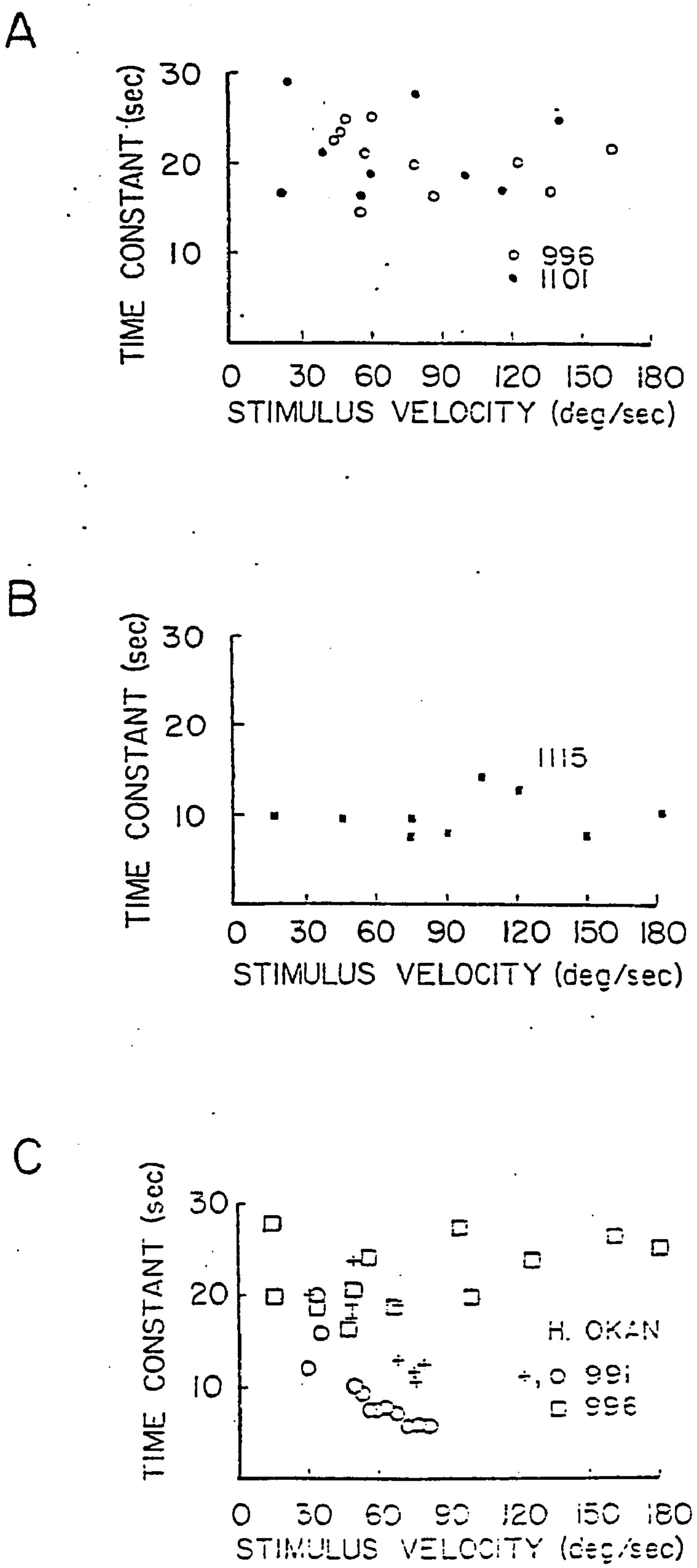
In summary, downward OKAN is vigorous and increases with increasing stimulus velocity to 60 to 70 deg/sec, whereas upward OKAN is weak or absent and rarely increases above 10 deg/sec, regardless of the preceding stimulus velocity (Fig. 15C). Horizontal OKAN is stronger than downward OKAN and has maximum values between 70-90 deg/sec (Fig. 15D). The functional significance of this is that there should be different amounts of stored activity for participation in visual-vestibular interactions for nystagmus in different planes.

Time constant of decay of vertical OKAN.

To estimate the time constant of decline of OKAN, the area under the OKAN response profile was integrated and divided by the starting velocity (see Methods section). For stimulus velocities from 20-160 deg/sec time constants of decline of downward OKAN were about 20 sec in 2 monkeys (996, 1101) (Fig. 16A) and about 10 sec in a third (1115) (Fig. 16B). In monkey 996 time constants of horizontal OKAN were similar to those of downward OKAN (squares, Fig. 16C). In these animals OKAN time constants did not vary with stimulus velocity as in monkey 991

Figure 16. Time constants of downward and horizontal OKAN. Time constants of the decline of slow phase velocity in darkness are shown. A shows the data of two animals whose time constants of downward OKAN were similar. The values were variable but ranged from 15 to 30 sec and were not related to stimulus velocity. B shows results of another animal with a time constant of about 10 sec. Here also, time constant of decline did not change with stimulus velocity. C shows time constants of horizontal OKAN for comparison. In one monkey (M 996) time constants ranged from 15 to 30 sec and showed no effect of stimulus velocity. In another, extensively tested animal (M 991), time constants appeared to decrease with increasing stimulus velocity. Further, time constants of right OKAN (circles) were shorter than those of leftward OKAN (crosses).

TIME CONSTANTS, DOWNWARD OKAN



(Fig. 16C). The time constant of decay of OKAN was affected by repeated testing. Naive animals generally had the longest time constants, and extensively tested animals (M 991) had the shortest time constants; peak velocities of OKAN were not affected by adaptation. Upward OKAN was generally so irregular in velocity that accurate estimates of the time constant of the responses were not possible although, as noted, when upward OKAN appeared, its duration could be similar to that of downward OKAN.

Charge characteristics of vertical OKN and OKAN.

Experiments were undertaken to measure the time course of the slow rise in OKN and the time over which the slow phase eye velocity of OKAN appeared. Brief periods of upward and downward OKN were given by rotating the drum at 45 deg/sec in darkness. The drum light was turned on for varying periods from 0.1 to 10 sec. The peak velocity of OKN and of OKAN induced by these periods of optokinetic stimulation was measured. The paradigm is shown in Fig. 17. The animal saw full field movement at 45 deg/sec for 2 sec. OKN eye velocity rose to 27 deg/sec. This is about 0.6 of the steady state OKN velocity reached during longer periods of stimulation. At the end of stimulation, slow phase velocity fell rapidly to 8 deg/sec or about 0.24 of the maximum steady state OKN velocity. The large drop after shorter periods of OKN can be compared to the much smaller drop shown in Fig. 8 when the stimuli lasted longer.

The effect of varying periods of stimulation at 45 deg/sec in inducing downward OKN and downward OKAN is shown in Figure 18 A,B, in

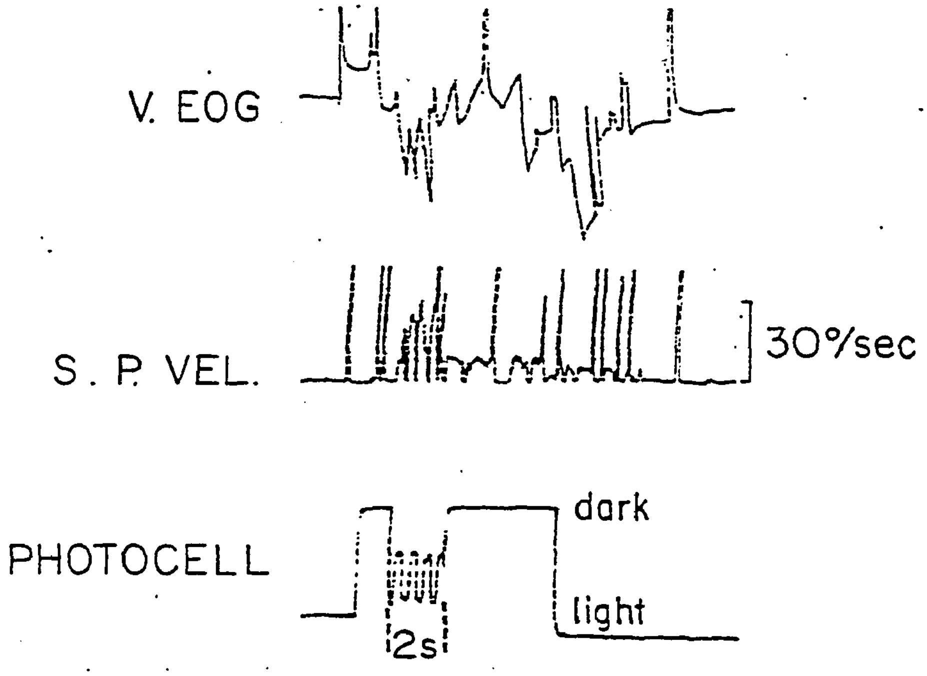


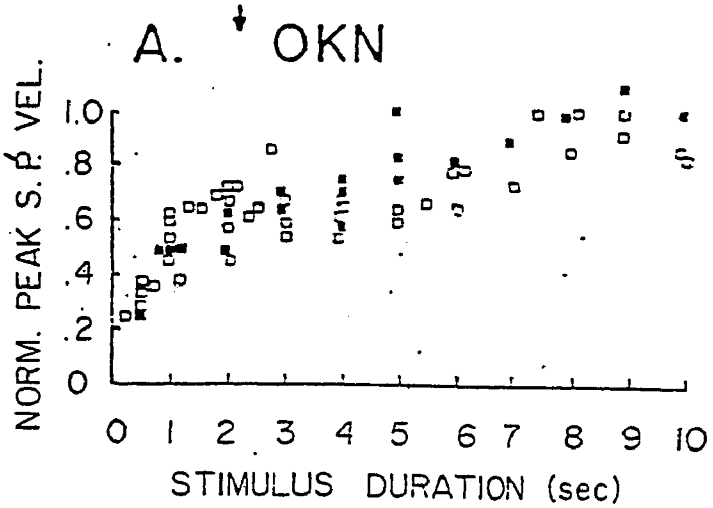
Figure 17. Charge of downward OKN and OKAN, experimental paradigm. The top trace is the vertical EOG. The second trace is vertical slow phase velocity. The third trace is the photocell. A 2 second, 45 deg/sec stimulus was given. Eye velocity increased quickly to about 27 deg/sec, then fell to about 8 deg/sec when the lights were out. For this series of experiments, stimulus duration varied from 100 msec to 10 sec.

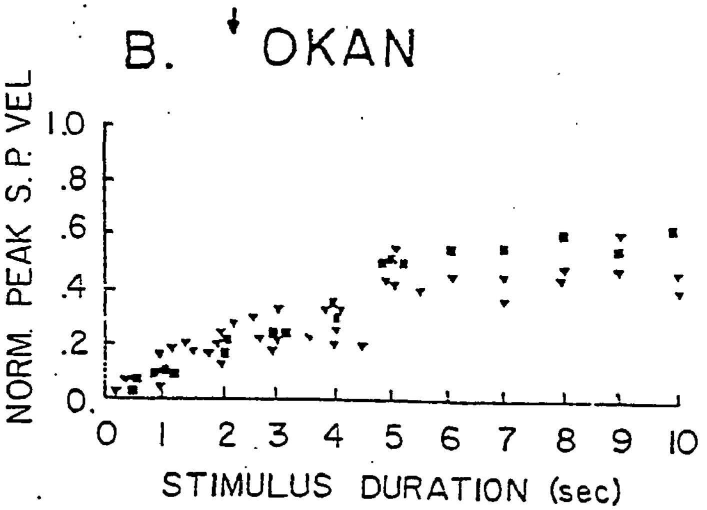
two monkeys (1111, 1118). The fast rise in slow phase velocity at the onset of downward OKN in both animals was 0.5 to 0.7 of the steady state velocity. Peak slow phase velocity of OKN increased gradually with increasing stimulus durations over 6 to 7 seconds (Fig. 18A). OKN slow phase velocity did not increase for periods of stimulation greater than 8 seconds.

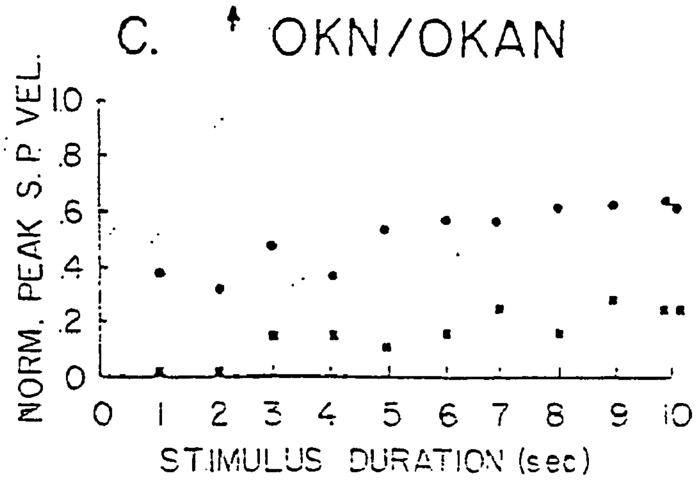
In response to these brief periods of stimulation the peak velocity of the slow phases of OKAN also increased with increasing stimulus duration (Fig. 18B). The increase also took 7 or 8 sec to reach a steady state level that was 0.5 to 0.6 of the steady state OKN level. The time course of the rise of OKAN slow phase velocity was 3.7 sec. This is the same as the time course of the slow rise in OKN velocity. This suggests that the same mechanism responsible for the slow rise in OKN velocity is involved in producing OKAN.

One monkey (M 1118) had weak upward OKAN. The charge characteristics of upward OKN and OKAN were studied in this animal. As with horizontal and downward OKN, there was a quick rise in slow phase velocity to about 0.4 of the normalized downward response (Figure 18C, circles). As the stimulus duration increased there was some evidence of a gradual rise to a steady state level over the first 5 to 6 sec. The steady state level of upward OKN in this animal was about 0.6 of the value reached during downward OKN for the same stimulus velocity. If the short pulse of upward optokinetic stimuli elicited upward OKAN, it decayed rapidly in 4 to 5 sec or less. Nevertheless the peak value of upward OKAN was normalized and plotted relative to stimulus duration (Figure 18, squares). As with downward OKAN there was a tendency for

Figure 18. Charge of downward and upward OKN and OKAN by full field rotation. A. Downward OKN charge. Each symbol represents a trial of drum rotation for a stimulus duration lasting from 100 msec to 10 sec. The data form a slowly rising monotonic function that could be approximated by an exponential with a time constant of 3.7 sec. B. Peak velocity of downward OKAN slow phase velocities also increase with increasing stimulus duration, with a time constant of about 3.7 sec. The symbols represent different monkeys. C. Charge of upward OKN and OKAN. The circles represent normalized peak velocities of OKN, and the squares represent normalized peak velocities of OKAN in one monkey. Stimulus durations were from 1 to 10 sec. The data form a monotonically rising function with an estimated time constant of 3.4 to 3.7 sec.


A. ↓ OKN


B. ↓ OKAN


C. ↑ OKN/OKAN

normalized peak velocities of OKAN to increase as the duration of stimulation increased, up to 6 to 7 sec. The time constants of rise of upward OKN and the appearance of OKAN were similar, being 3.4 and 3.7 sec, respectively.

To permit a comparison of charge characteristics of vertical with horizontal nystagmus, the time course of the slow rise in OKN velocity is shown in Fig. 19 and the charge of OKAN of another monkey (M 991) is shown in Fig. 20. In each instance the time course of the slow rise in OKN and the charge of the OKAN mechanism was similar. As noted previously, charge times increased somewhat with increases in slow phase velocity (Cohen et al., 1977). The significance of this slight increase in charge time dependent on velocity is unknown.

Visual suppression of OKAN.

If the stationary optokinetic drum is illuminated for brief periods during OKAN, slow phase velocity drops and does not fully recover when the animals are again in darkness. The effect of varying duration of exposure to a stationary environment on OKAN recovery velocity was tested in 2 animals. Figure 21A shows the experiment. The optokinetic stimulus was a 40 deg/sec step of downward velocity. After stimulation, the animal was in darkness for 3 sec. Then the light was turned on for 4 sec exposing a stationary visual surround. Slow phase velocity fell during the suppression interval (see arrow) but rose again when the animal was in darkness. The effects of visual suppression could not be tested during upward OKAN since it was either absent or too weak to

Figure 19. Charge of horizontal OKN. These data are presented for comparison to vertical OKN charge data. Brief periods of optokinetic stimuli from 30 to 105 deg/sec were given. Normalized peak slow phase velocity is plotted versus stimulus duration. Data are from M 991.

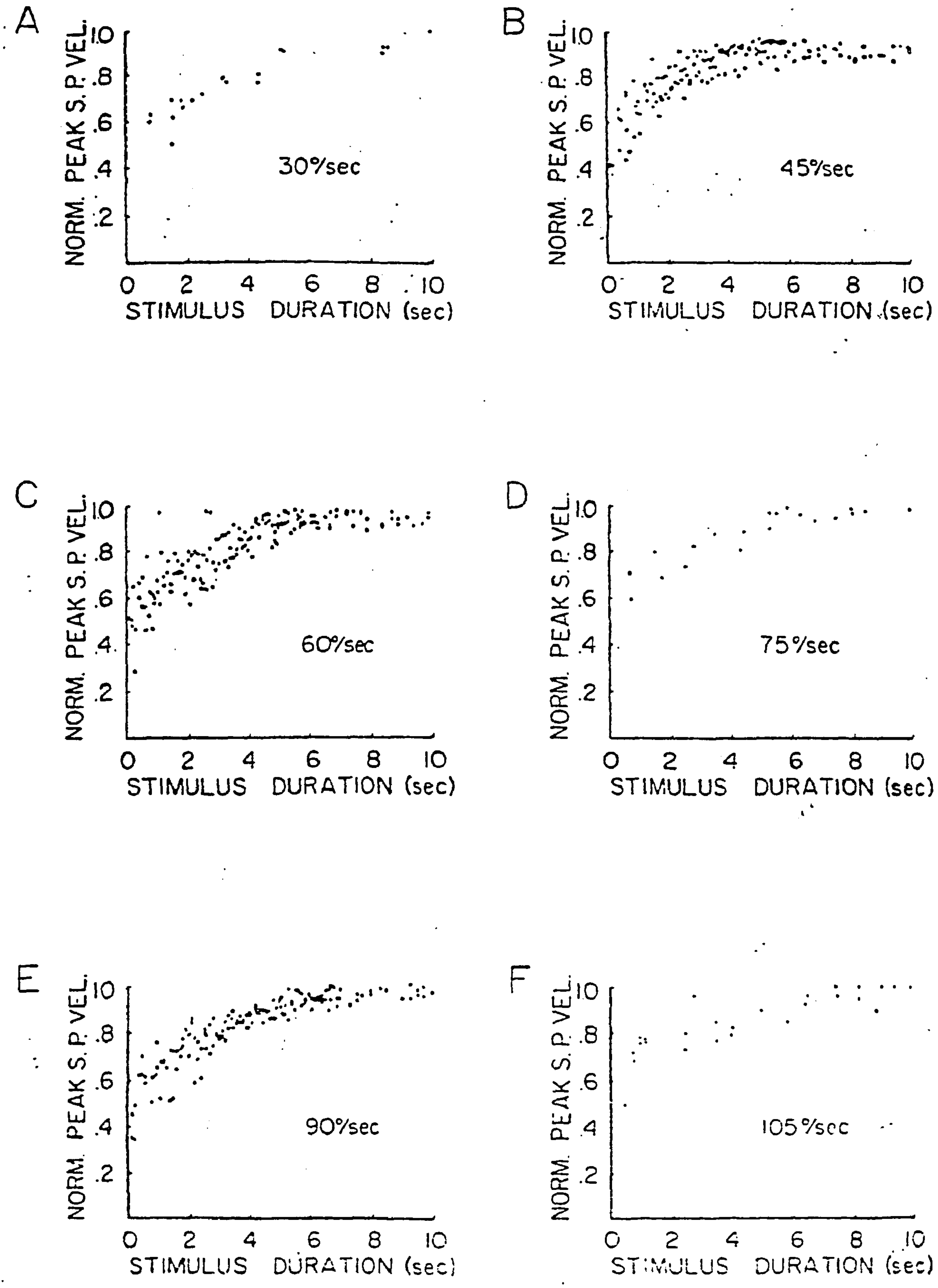

A
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
0
2
4
6
8
10
STIMULUS DURATION (sec)
30°/sec
B
NORM. PEAK S.P. VEL.
45°/sec
STIMULUS DURATION (sec)
C
NORM. PEAK S.P. VEL.
60°/sec
STIMULUS DURATION (sec)
D
NORM. PEAK S.P. VEL.
75°/sec
STIMULUS DURATION (sec)
E
NORM. PEAK S.P. VEL.
90°/sec
STIMULUS DURATION (sec)
F
NORM. PEAK S.P. VEL.
105°/sec
STIMULUS DURATION (sec)

Figure 20. Charge of horizontal OKAN. These data are from the same experiments as those in the Figure 19. After the drum light was turned off, peak OKAN values were normalized and plotted versus stimulus duration. The charging time constants tended to increase with increasing stimulus velocity.

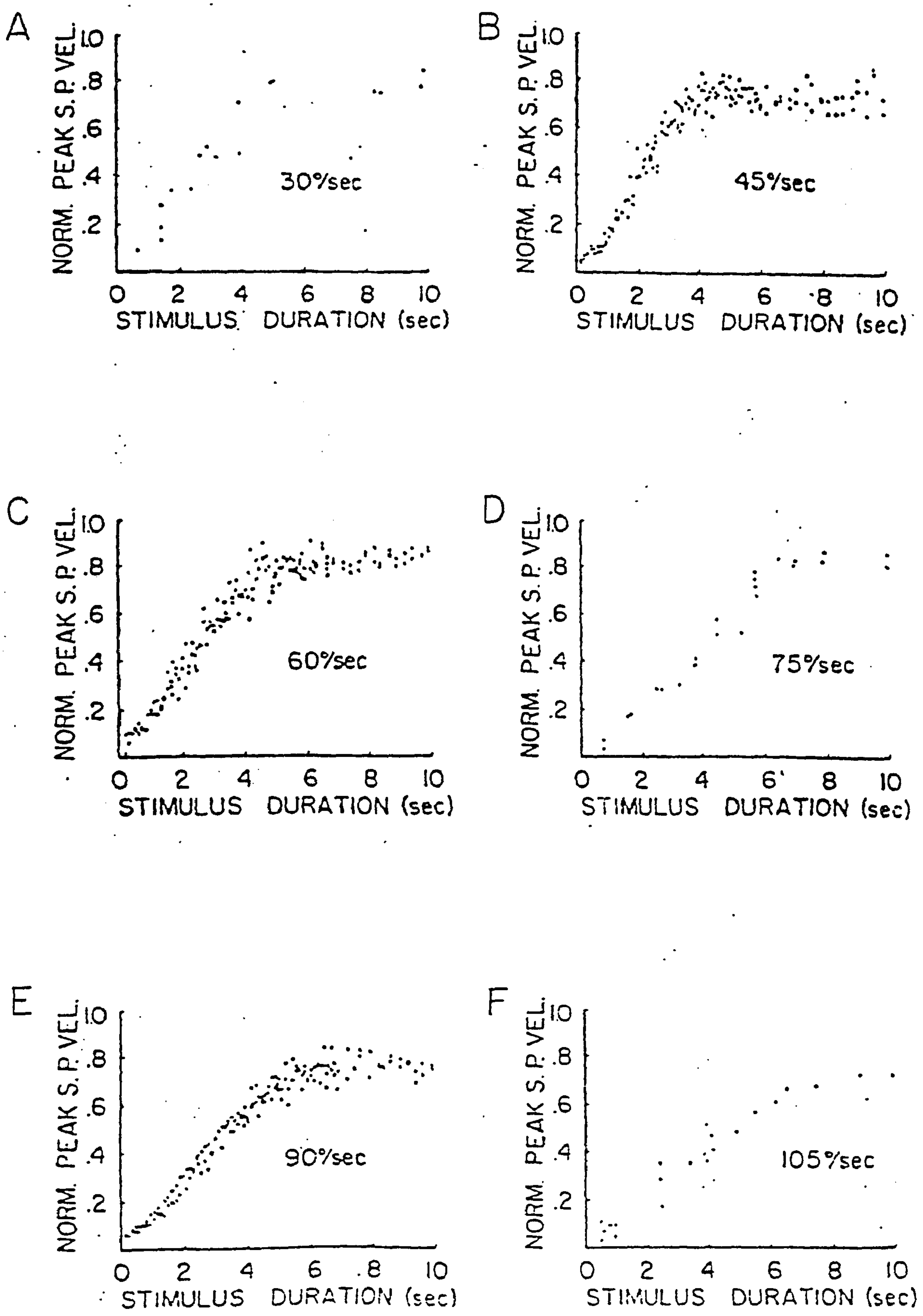
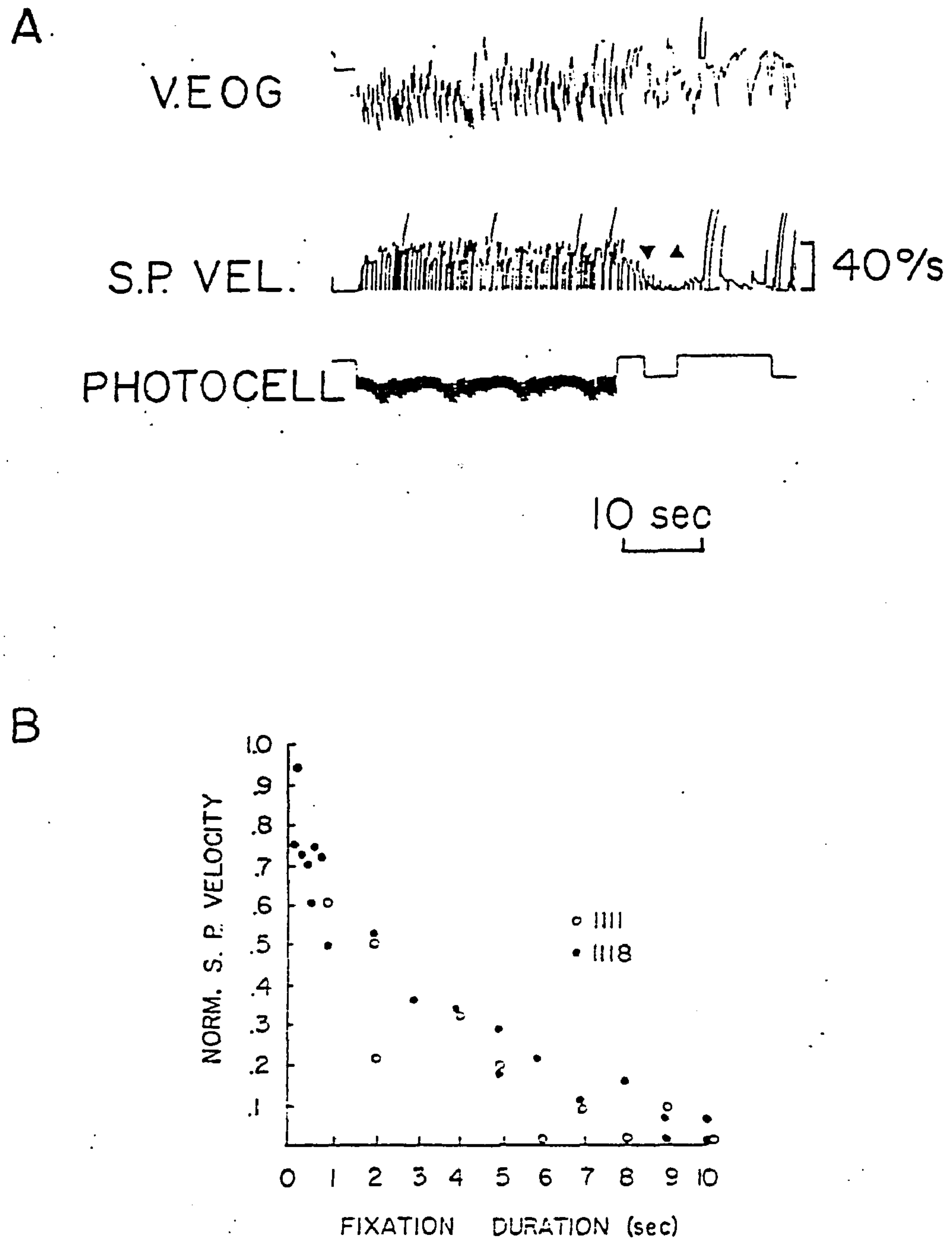

A
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
30°/sec
0
2
4
6
8
10
STIMULUS DURATION (sec)
B
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
45°/sec
0
2
4
6
8
10
STIMULUS DURATION (sec)
C
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
60°/sec
0
2
4
6
8
10
STIMULUS DURATION (sec)
D
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
75°/sec
0
2
4
6
8
10
STIMULUS DURATION (sec)
E
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
90°/sec
0
2
4
6
8
10
STIMULUS DURATION (sec)
F
NORM. PEAK S.P. VEL.
1.0
.8
.6
.4
.2
105°/sec
0
2
4
6
8
10
STIMULUS DURATION (sec)

Figure 21. Visual suppression of downward OKAN. A. Experimental paradigm. Top trace is vertical EOG, middle trace is slow phase velocity and bottom trace is photocell signal. Three seconds after the end of optokinetic stimulation, the drum light was turned on for 4 sec (downward arrow). Slow phase velocity decreased during the period and rose again slowly when the animal was in darkness (upward arrow). B. The peak OKAN slow phase velocity just after the period of vision was divided by the peak OKAN slow phase velocity just before the period of vision for intervals from 100 msec to 10 sec. This value is plotted versus interval duration, and describes a monotonically declining function that could be approximated by an exponential with a time constant of 3 to 4 sec.


A
V.EOG
S.P. VEL.
40°/s
PHOTOCELL
10 sec
B
NORM. S. P. VELOCITY
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
3
4
5
6
7
8
9
10
FIXATION DURATION (sec)
○ 1111
● 1118

measure.

Data from another animal for horizontal nystagmus are shown in Fig. 22A. Two differences were present in suppression of downward and horizontal OKAN. First, slow phase velocity fell faster at the onset of the period in light for horizontal than for vertical nystagmus. Secondly, the amount of activity that was lost after a 4 second period of suppression of downward nystagmus was about the same as for a 2 second period of suppression of horizontal nystagmus. This suggests that the suppression mechanism is more effective for horizontal than for downward nystagmus.

Effects of varying periods of visual suppression on downward nystagmus on 2 animals are shown in Fig. 21B. In both animals slow phase velocity decreased with increasing fixation duration falling to zero over 8 to 10 sec. The data could be approximated by an exponential with a time constant of 3 to 4 sec. This is about 3 times as long as the time constant of visual suppression of horizontal OKAN (Fig. 22B).

In summary, there is a marked asymmetry in upward and downward OKN and OKAN in the monkey. Downward OKN and OKAN are stronger than upward nystagmus. Downward and horizontal OKN and OKAN were comparable. Visual suppression was more effective in reducing stored activity of horizontal than downward nystagmus.

Vestibular nystagmus.

When animals were given a step of velocity about a vertical interaural axis in darkness, characteristic vestibular nystagmus was

Figure 22. Visual suppression of horizontal OKAN. A. Experimental paradigm. After 60 deg/sec optokinetic stimulation, OKAN was recorded in darkness for about 3 sec. The drum light was turned on for 1.8 sec and then turned off again. During the interval slow phase velocity fell, but recovered when the animal was in darkness (arrow). The recovery level was lower than the level of OKAN that would have been seen had no suppression occurred (dotted line). B. Data from an experiment similar to the one above. The ratio of the recovery velocity to the velocity just before the period of vision is plotted versus interval duration. The time constant of decline of OKAN during visual suppression was about 1.7 sec.

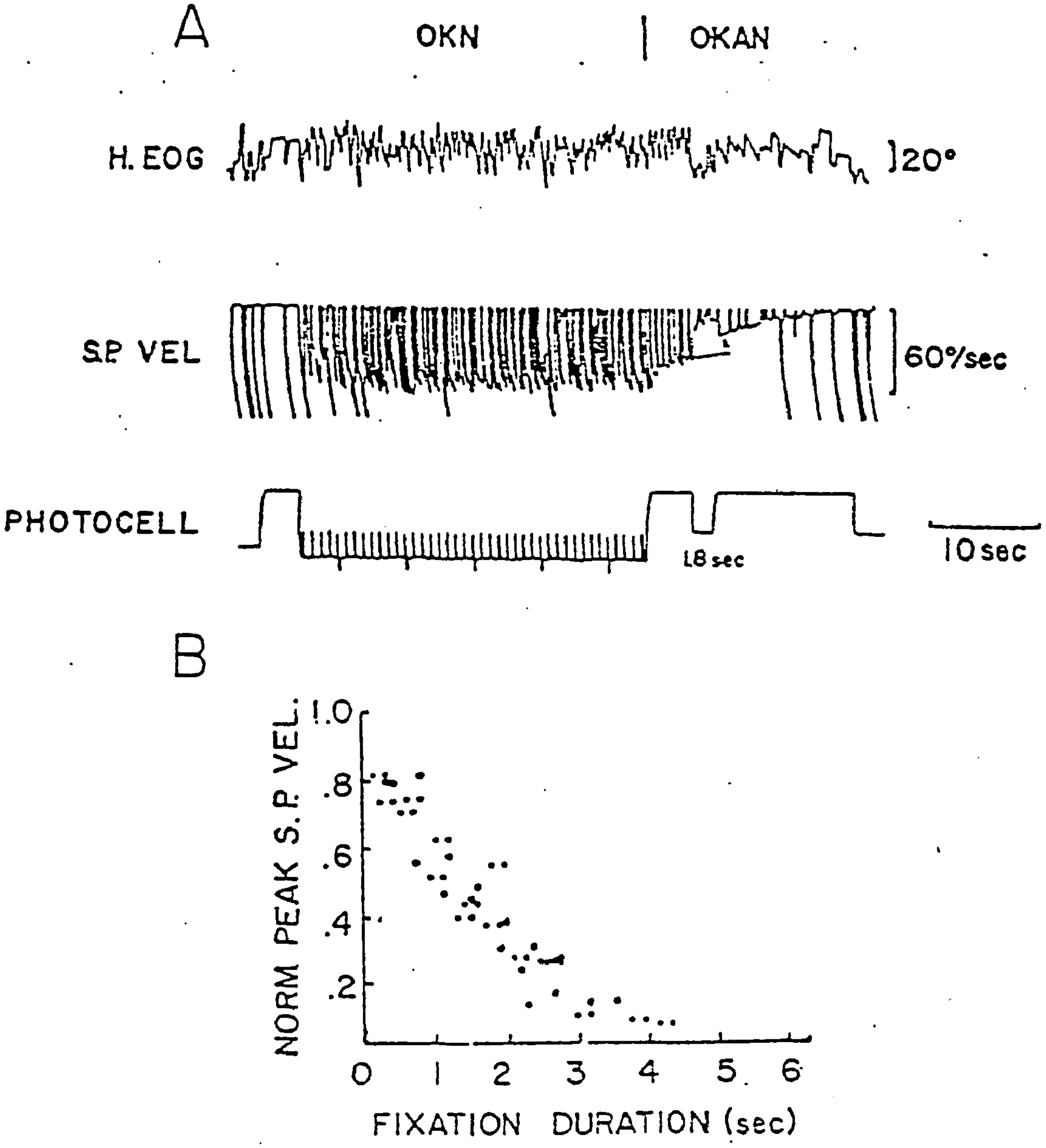
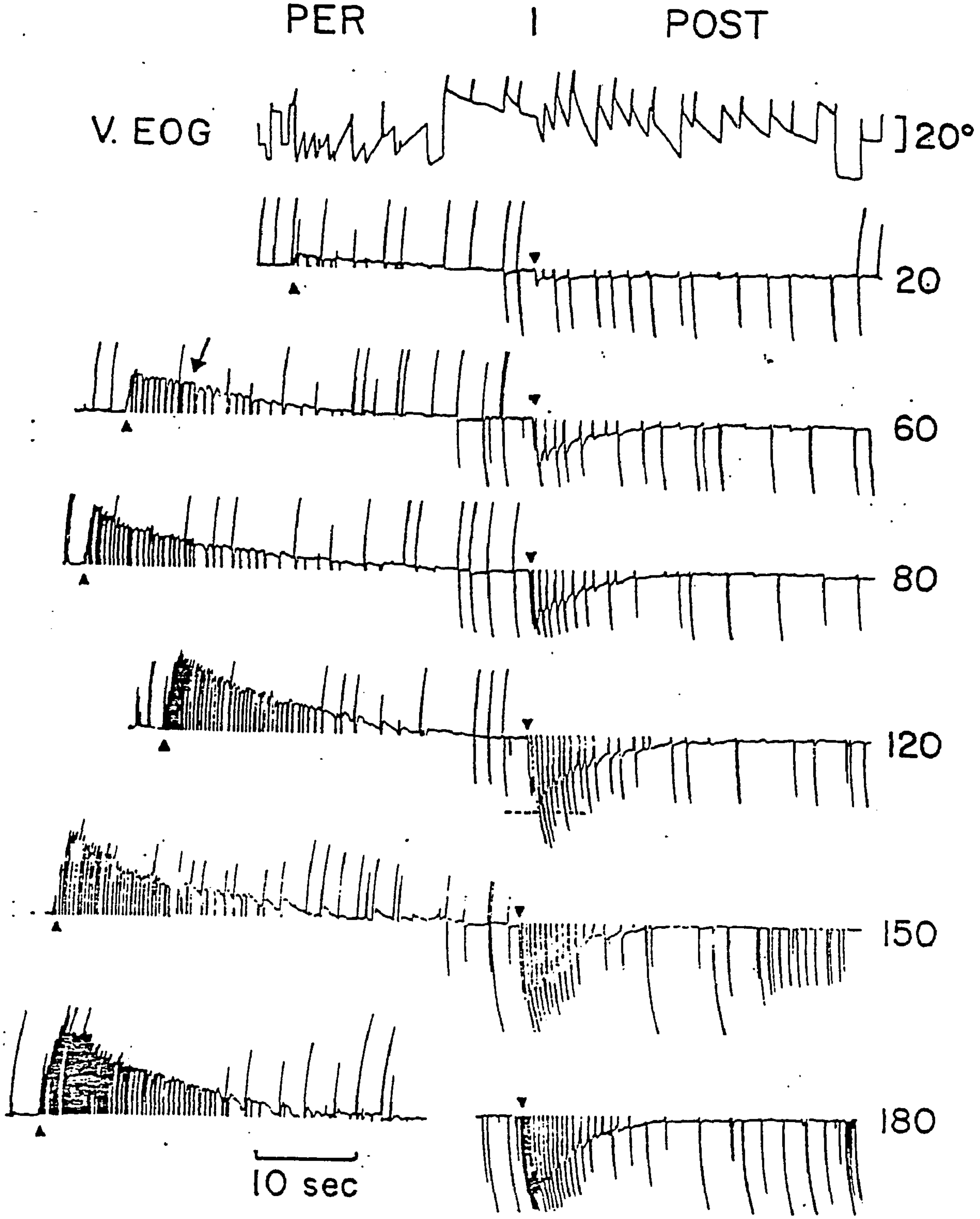

A
OKN
OKAN
H. EOG
20°
S.P VEL
60°/sec
PHOTOCELL
1.8 sec
10 sec
B
NORM PEAK S.P. VEL.
1.0
.8
.6
.4
.2
0
1
2
3
4
5
6
FIXATION DURATION (sec)

Figure 23. Vertical VOR in darkness. These are typical examples of the response to a step of velocity in darkness. The top trace is the vertical EOG. The traces below are the slow phase velocity of vertical vestibular nystagmus. The numbers in the right hand column refer to the stimulus velocity. This figure shows that the peak gain of upward and downward nystagmus are about the same, excluding lid artifacts. The duration of downward nystagmus exceeds that of upward nystagmus. Note the slight "plateau" of slow phase velocity at 60 deg/sec (diagonal arrow). Upward and downward arrows show the point of acceleration and deceleration at the beginning and end of the velocity step. Dotted line points to the peak velocity.


PER
I
POST
V. EOG
]20°
20
60
80
120
150
180
10 sec

induced (Fig. 23). It was similar in many respects to horizontal vestibular nystagmus (Fig. 24). At the onset of an upward or downward velocity step in darkness the eyes moved in the compensatory direction. Peak velocity was usually reached within several beats and then declined gradually over 10 to 60 sec. There is a "plateau" of velocity in horizontal vestibular nystagmus, that is a manifestation of stored activity (Fig. 24 arrows) (Raphan et al., 1979). It was present during downward nystagmus (Fig. 23, diagonal arrow), but was absent during upward nystagmus. A prominent difference between upward and downward vestibular nystagmus was that upward nystagmus was considerably shorter than downward nystagmus; its frequency was also lower.

After excluding blink artifacts peak slow phase velocities of vertical vestibular nystagmus were measured and plotted as a function of platform velocity. They increased linearly with increasing stimulus velocity with a gain that was approximately 1.0 for stimulus velocities from 10 to 150 deg/sec (Fig. 25A). Upward and downward peak velocities were equal in magnitude and were similar in gain to velocities of horizontal vestibular nystagmus (Fig. 25B).

Normalized peak velocities of vertical per and post rotatory nystagmus were measured in three monkeys (Z-P, 993, 1101) (Fig. 25A). Group means increased with increases in stimulus velocity between 10 and 150 deg/sec with a gain of 0.99 (Fig. 25C). Upward and downward slow phases reached similar velocities during the peaks of vestibular nystagmus. Gains during vertical vestibular nystagmus were similar to those during horizontal nystagmus (Fig. 25B, D) with one exception. At the highest stimulus velocities, the horizontal gain was higher than

Figure 24. Horizontal VOR in darkness. The top trace is the horizontal EOG, and the next four traces are the slow phase velocity. Note that peak slow phase velocity increased with increases in stimulus velocity. Note also the prominent "plateau" at 51 deg/sec (diagonal arrows).

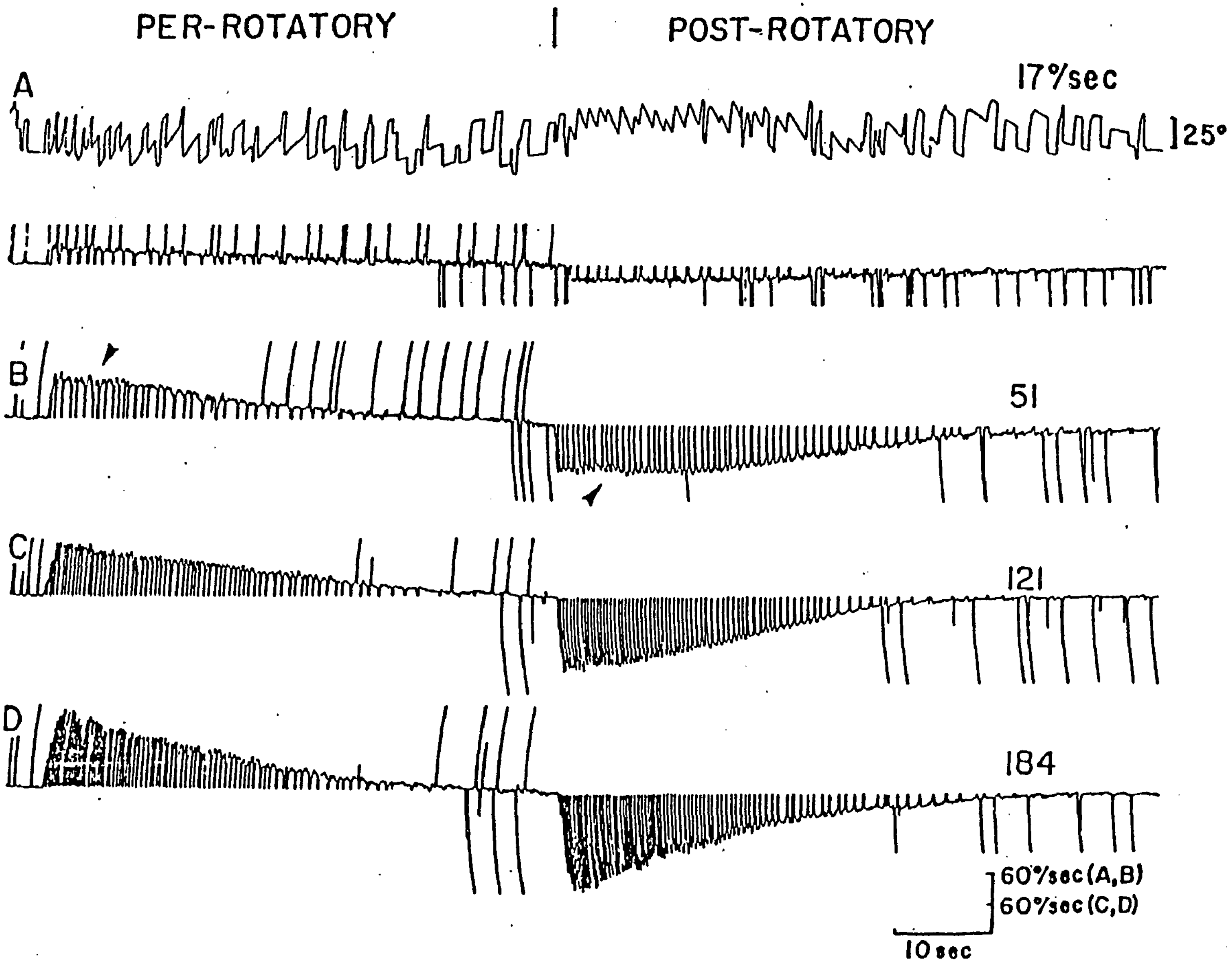
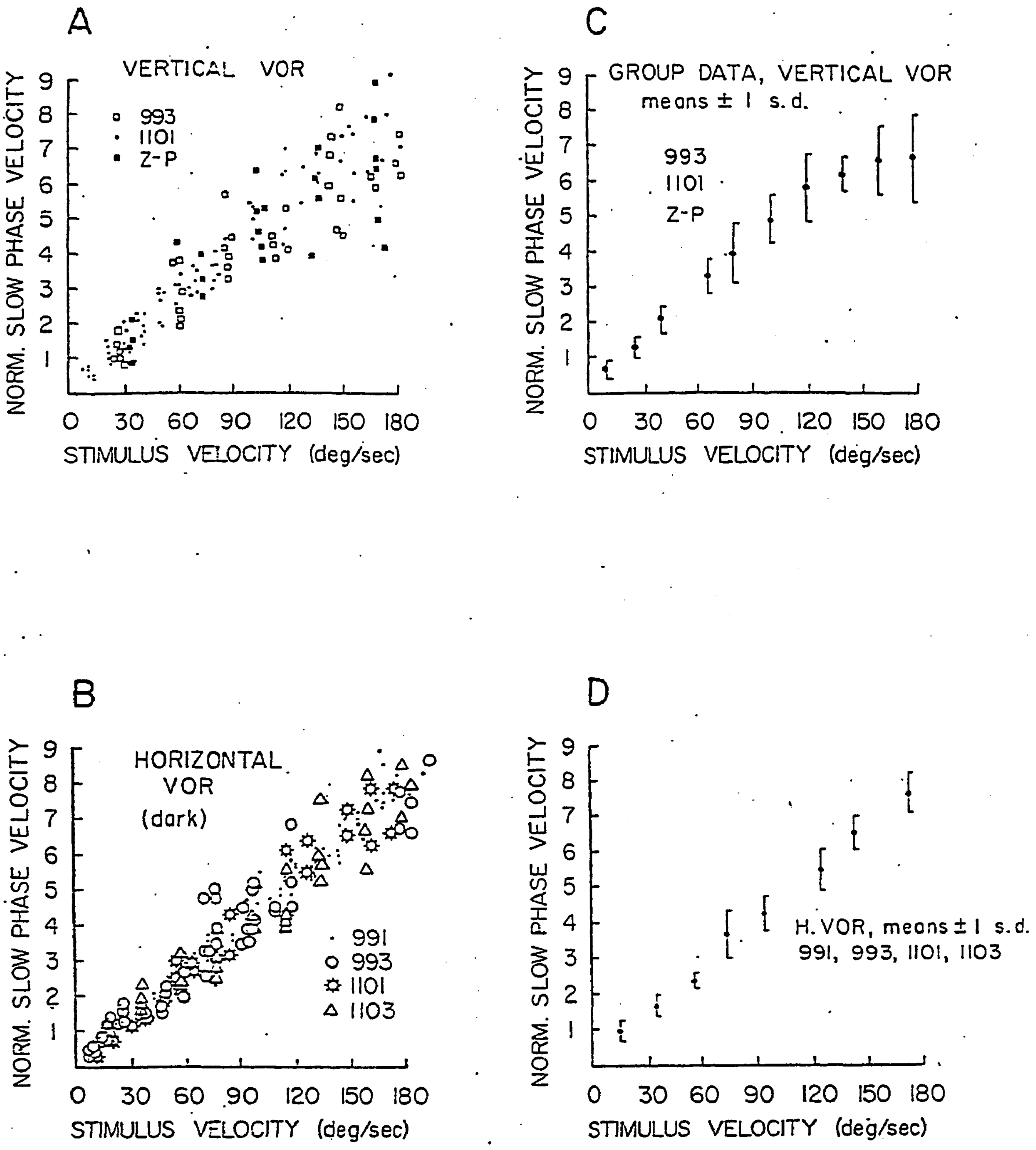

PER-ROTATORY
POST-ROTATORY
A
17°/sec
25°
B
51
C
121
D
184
60°/sec (A,B)
60°/sec (C,D)
10 sec

Figure 25. Vertical and horizontal VOR, group data. A,C. Vertical VOR, grouped individual data and means and standard deviations, respectively. Note that the gain of the vertical VOR is near 1 up to 140 deg/sec. B,D. Horizontal VOR, grouped data and means and standard deviations of the grouped data, respectively. Note that except for the highest stimulus velocity, the gains of the horizontal and vertical VOR are similar.

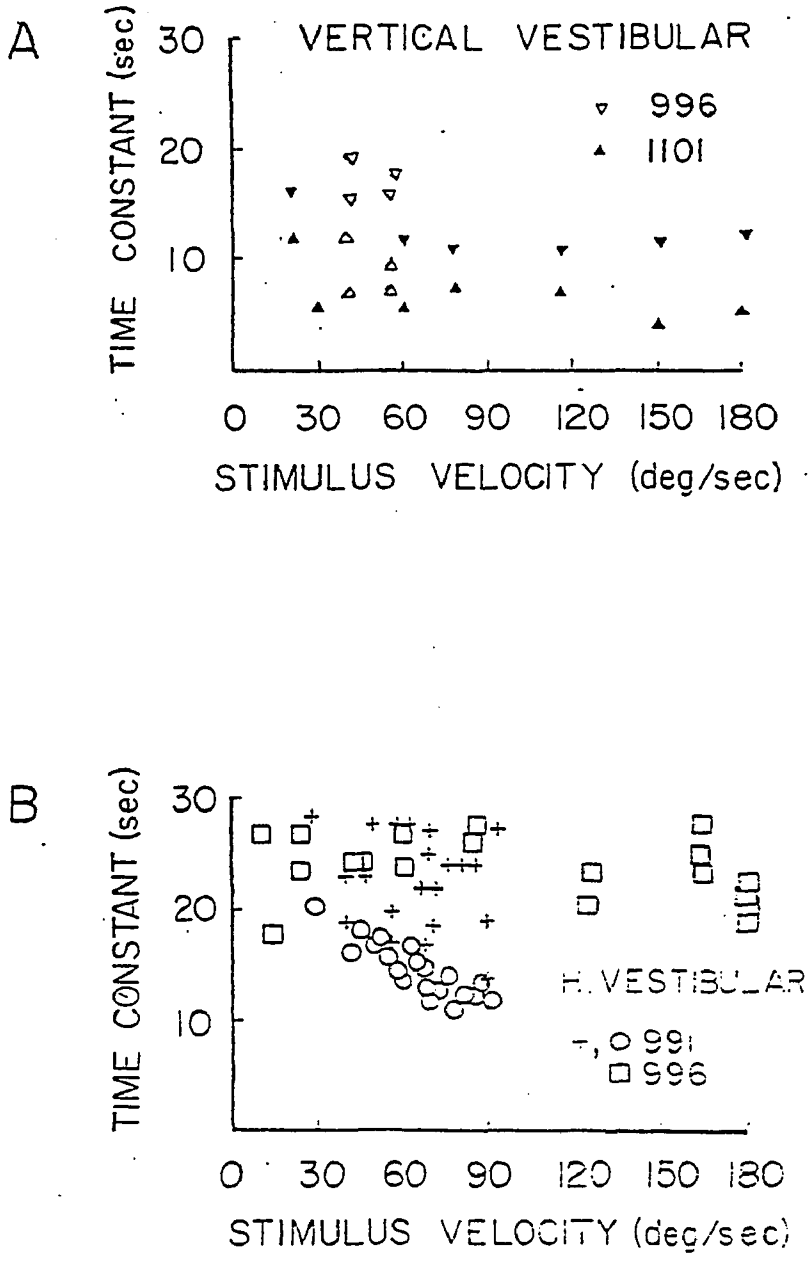

A
VERTICAL VOR
993
1101
Z-P
NORM. SLOW PHASE VELOCITY
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)
C
GROUP DATA, VERTICAL VOR
means ± 1 s.d.
993
1101
Z-P
NORM. SLOW PHASE VELOCITY
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)
B
HORIZONTAL VOR (dark)
991
993
1101
1103
NORM. SLOW PHASE VELOCITY
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)
D
H. VOR, means ± 1 s.d.
991, 993, 1101, 1103
NORM. SLOW PHASE VELOCITY
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)

vertical gain.

Time constants of vertical vestibular nystagmus.

The asymmetry in vertical nystagmus shown in Fig. 23 appears to be related to asymmetrical storage of activity related to slow phase velocity during upward and downward nystagmus. This is supported by estimates of time constants. In two monkeys (996, 1101) time constants of downward nystagmus (downward arrows) ranged from approximately 16 sec at 20 deg/sec to about 12 sec at 180 deg/sec (Fig. 26). They were consistently longer than those of upward nystagmus (upward arrows) which ranged from about 10 sec at 20 deg/sec to 5 sec at 180 deg/sec. In the monkey that received the most extensive vertical testing (1101) time constants of upward vestibular nystagmus were approximately 5 sec for all stimulus velocities above 30 deg/sec. This value is close to the time constant of activity in the vestibular nerve in response to a velocity step deflection of the cupula (Goldberg and Fernandez, 1971). Since the time constants of downward nystagmus were comparable in magnitude to those of horizontal nystagmus (Fig. 26B) it indicates that both downward and horizontal nystagmus are prolonged beyond the duration of the VIIIth nerve activity induced by the step of velocity whereas upward nystagmus is not. This suggests that storage of activity related to slow phase eye velocity has little influence in production of upward nystagmus.

Figure 26. Time constants of vertical and horizontal VOR. A. Vertical VOR time constants in two monkeys are plotted versus stimulus velocity. Downward arrows refer to downward nystagmus, upward arrows to upward nystagmus. Note that time constants of downward nystagmus are always longer than those for upward nystagmus. Downward time constants ranged from 10 to 20 sec whereas upward time constants were frequently near 5 sec. B. Time constants of horizontal VOR. Time constants in one monkey (M 996) were 20 to 30 sec and showed no effect of stimulus velocity. Time constants in another, extensively tested animal (M 991) showed a strong influence of stimulus velocity on VOR time constant, especially for rightward vestibular nystagmus (circles).


A
TIME CONSTANT (sec)
30
20
10
VERTICAL VESTIBULAR
▿ 996
▴ 1101
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)
B
TIME CONSTANT (sec)
30
20
10
H. VESTIBULAR
+, ○ 991
□ 996
0
30
60
90
120
150
180
STIMULUS VELOCITY (deg/sec)

Visual suppression of vertical vestibular nystagmus.

Visual suppression during vertical vestibular nystagmus was investigated in two animals (993, 1101). Animals were given vertical steps of velocity at 60 deg/sec in darkness. When the per rotatory response had subsided, the rotation was stopped. After a 2 to 3 second period the lights were switched on to expose a stationary surround. When this occurred, slow phase velocity declined suddenly for the duration of the exposure. Provided the exposure duration was sufficiently short, slow phase velocity rose when the animal was again in darkness. The experimental paradigm is illustrated in Fig. 27. The fixation period in both examples was 1 sec. There was asymmetry in the effects of visual suppression during upward (A) and downward (B) vestibular nystagmus. This was a systematic effect (Fig. 28). In two monkeys, exposure durations of 5 to 7 sec almost completely abolished upward nystagmus (B, D), whereas 10 to 12 sec were needed to suppress downward nystagmus (A, C). Time constants of decline were 7 to 8 sec for downward nystagmus, and about 3.5 sec for upward nystagmus in each monkey. This can be contrasted to similar data taken during horizontal post rotatory nystagmus for another monkey (Fig. 29). The curve of decline in recovery velocity had a time constant of 3 seconds which is similar to that of upward nystagmus. This is consistent with findings during visual suppression of OKAN (Fig. 21). Suppression was less effective for downward nystagmus, i.e., for nystagmus with upward slow phases, than for horizontal nystagmus.

In summary, velocity steps through an interaural, earth-vertical

Figure 27. Visual suppression of vestibular nystagmus, experimental paradigm. Visual suppression of upward (A) and downward (B) vestibular nystagmus are shown for a 1 second period of light. During the interval eye velocity dropped, but recovered again when the animal was in darkness. The drop was smaller and the recovery greater, for downward vestibular nystagmus. The time course of vestibular nystagmus without visual suppression is shown for comparison.

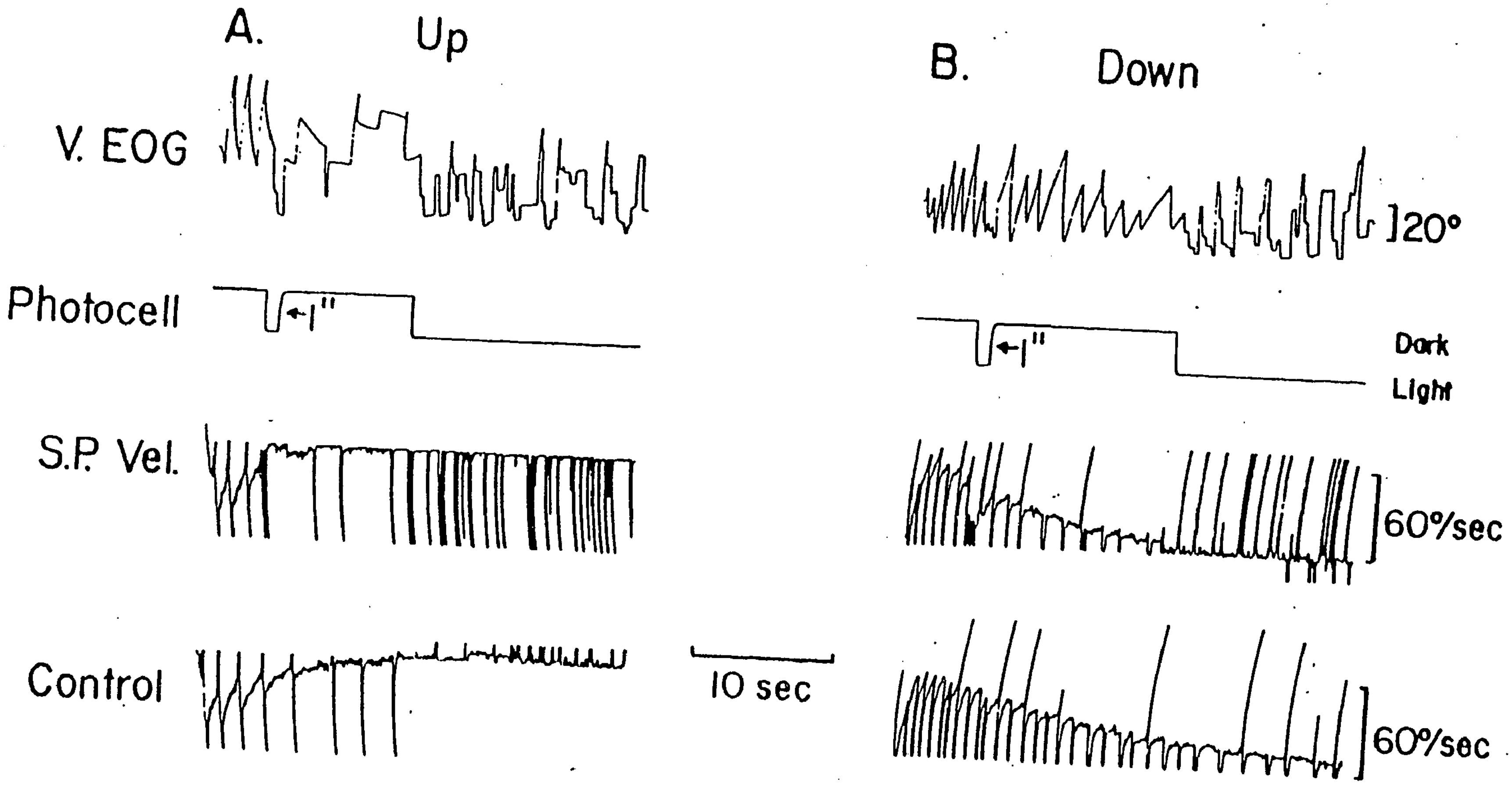

A.
Up
B.
Down
V. EOG
Photocell
S.P. Vel.
Control
←1"
←1"
]20°
Dark
Light
]60°/sec
]60°/sec
10 sec

Figure 28. Visual suppression of vertical vestibular nystagmus. Data from experiments similar to the one in Figure 27 are plotted for downward (A,C) and upward (B,D) nystagmus in two monkeys. Normalized peak slow phase velocities were calculated as for OKAN. Note that upward nystagmus is almost completely abolished by 8 sec of vision, whereas 12 sec or more are needed to suppress downward nystagmus.

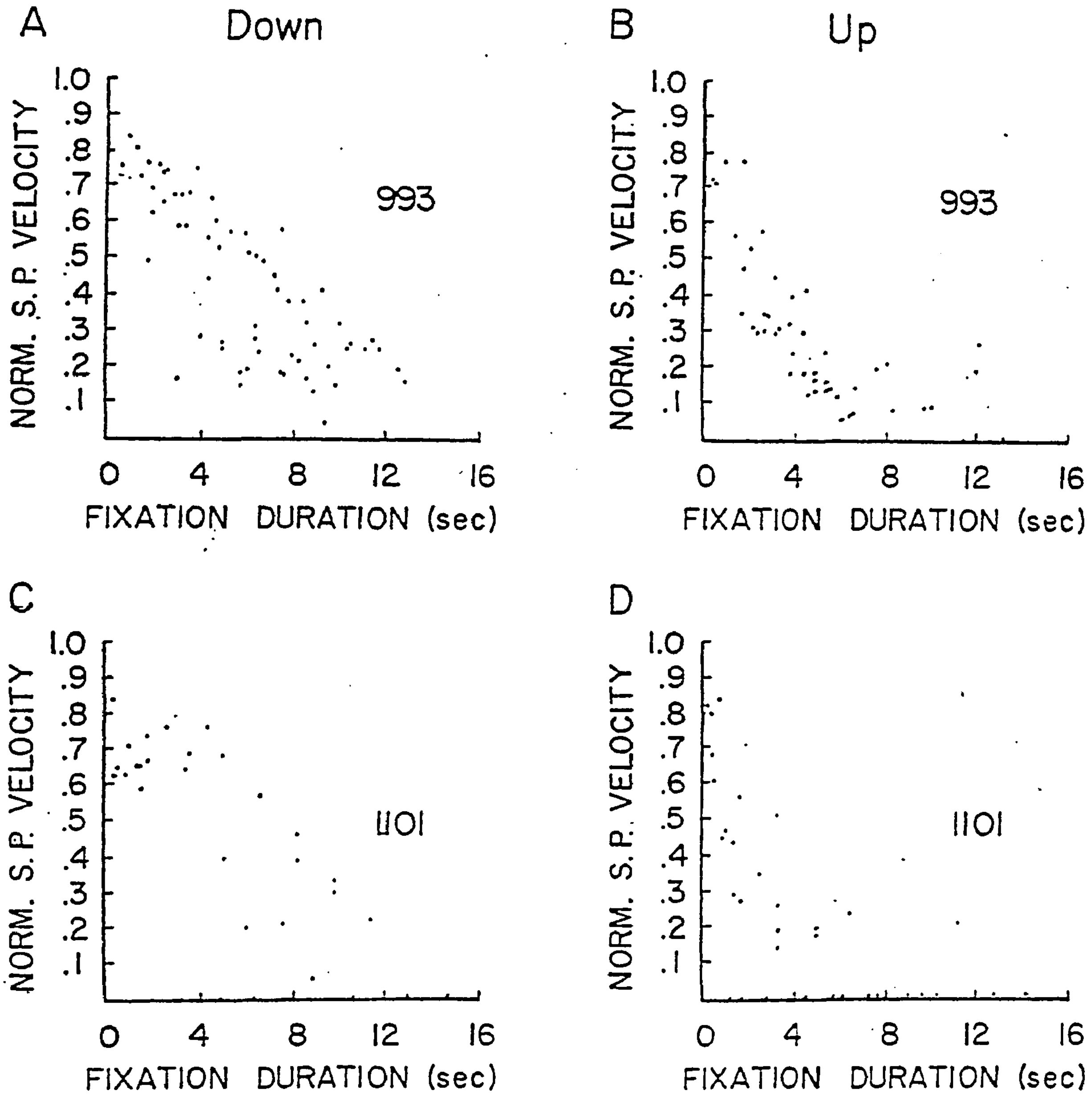
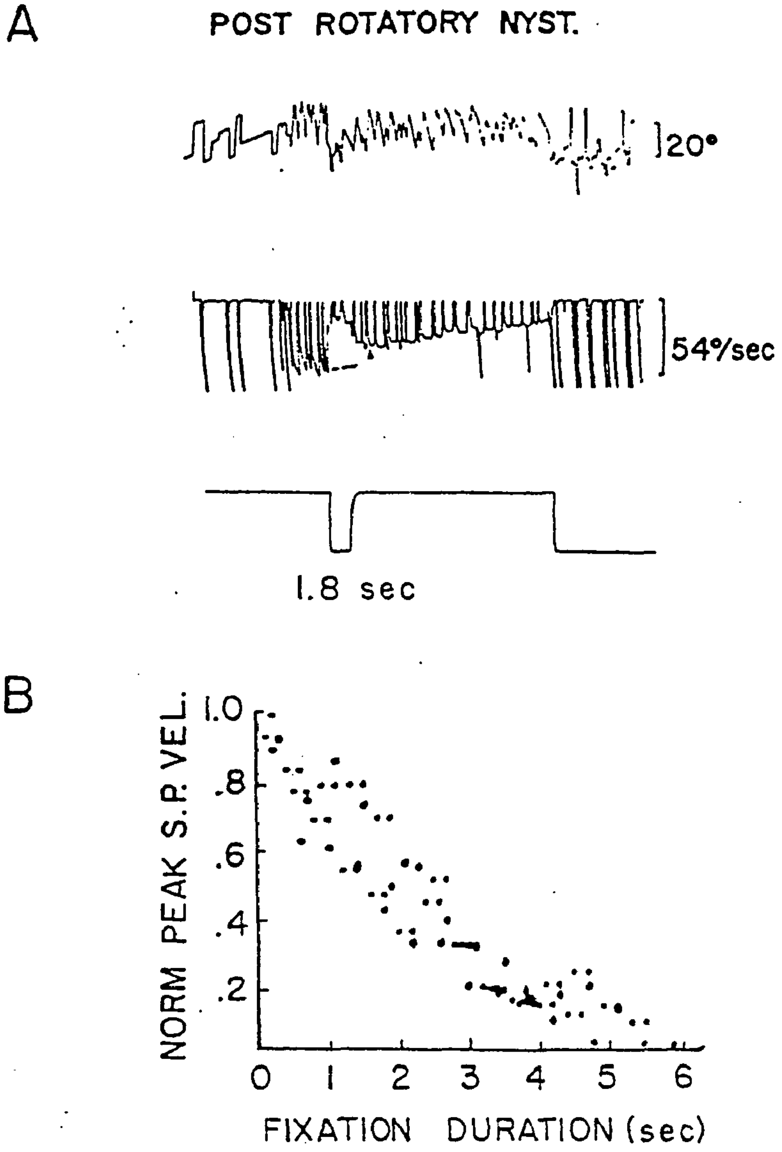

A
Down
B
Up
NORM. S.P. VELOCITY
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
993
0
4
8
12
16
FIXATION DURATION (sec)
C
D
1101

Figure 29. Visual suppression of horizontal vestibular nystagmus. A shows the experimental paradigm, which is identical to the one in Figure 27. The top trace is horizontal eye position, the second trace is slow phase velocity and the bottom trace is the photocell. The ratio of the recovery velocity (arrow) to the slow phase velocity immediately before suppression (dotted line) was plotted versus interval duration in B. Note that the visual suppression of horizontal vestibular nystagmus is similar to that of upward nystagmus and considerably more effective than visual suppression during downward nystagmus. Periods of 6 sec or longer completely abolished horizontal vestibular nystagmus in this monkey.


A
POST ROTATORY NYST.
20°
54°/sec
1.8 sec
B
NORM PEAK S.P. VEL.
1.0
.8
.6
.4
.2
0
1
2
3
4
5
6
FIXATION DURATION (sec)

axis were shown to induce peak compensatory eye velocities that were similar for upward and downward nystagmus. These values were similar to compensatory horizontal eye velocities induced by rotation in the upright position about a vertical axis. Although the initial compensatory upward and downward velocities were the same, the duration of upward nystagmus was shorter than that of downward nystagmus and its time constants of decline were in the range of activity generated in the vestibular nerve by steps of velocity. Time constants of downward nystagmus were longer, and were similar to those of horizontal nystagmus. This suggests that there is stored activity related to slow phase eye velocity associated with downward but not with upward nystagmus. In addition, visual suppression of nystagmus was shown to be less effective for downward than upward nystagmus.

Visual-vestibular interaction in vertical nystagmus.

When an animal is rotated in a lighted structured environment, both OKN and vestibular nystagmus are provoked. At the end of rotation post rotatory nystagmus and optokinetic after nystagmus are induced simultaneously. As noted earlier the after responses are in opposite directions and tend to cancel each other. This is demonstrated for horizontal nystagmus at 2 velocities, 60 and 180 deg/sec (Figs. 30C and 31C). If the interpretation of the after response as a summation of OKAN and post rotatory nystagmus is correct, the asymmetry in the ability to store activity related to slow phase velocity for vertical nystagmus should materially affect the strength of the after response.

Figure 30. Characteristics of horizontal nystagmus at 60 deg/sec. Vestibular (A), optokinetic (B) and visual-vestibular responses (C) are shown in one monkey. Note that visual-vestibular responses reflect attributes of vestibular and optokinetic nystagmus. The sharp rise in slow phase velocity and maintained steady state velocity for prolonged stimulation are followed by almost complete suppression of nystagmus at the end of rotation. Note that the post rotatory response and OKAN are almost equal in amplitude but opposite in sign. They cancel each other at the end of stimulation.

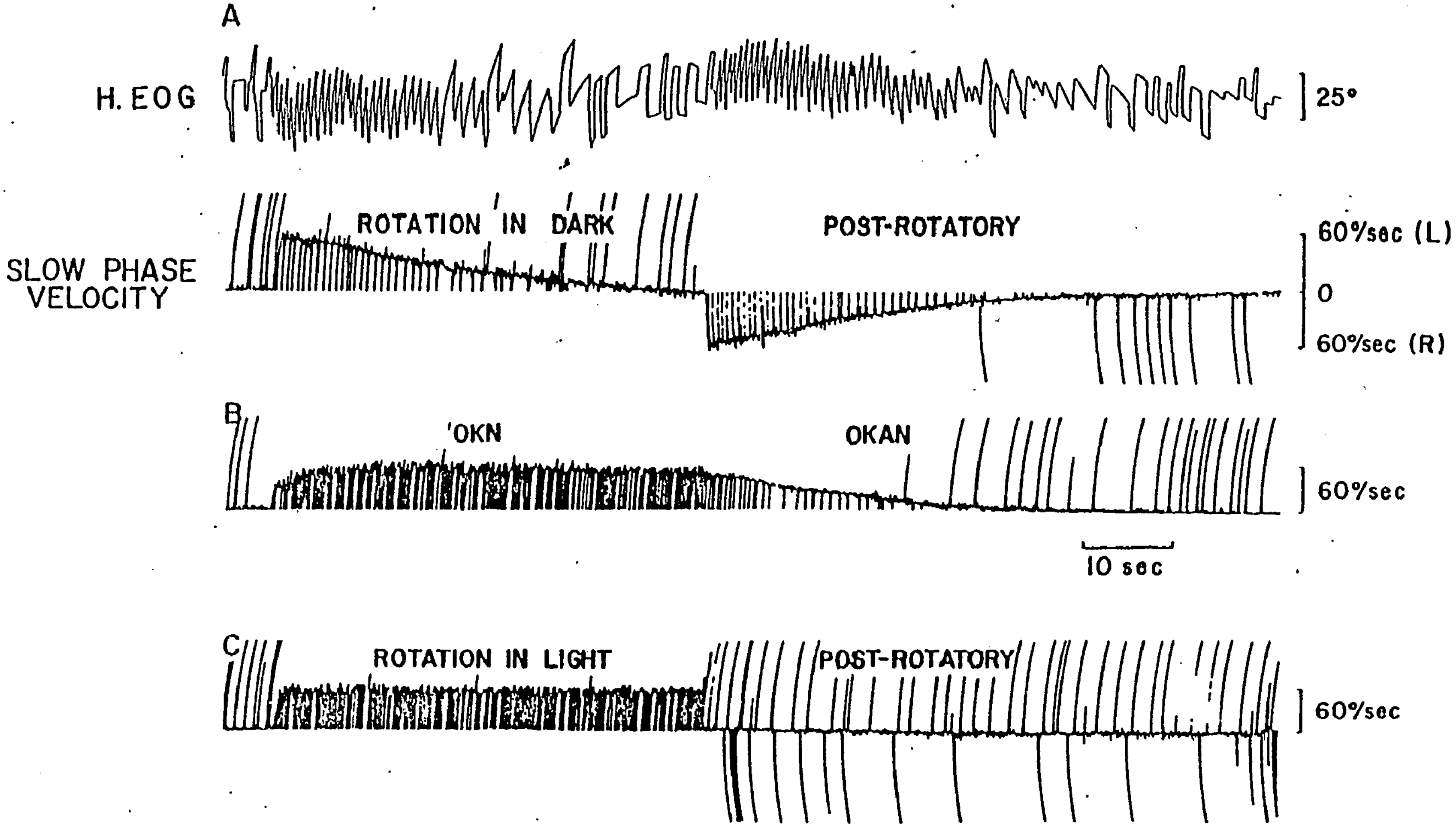
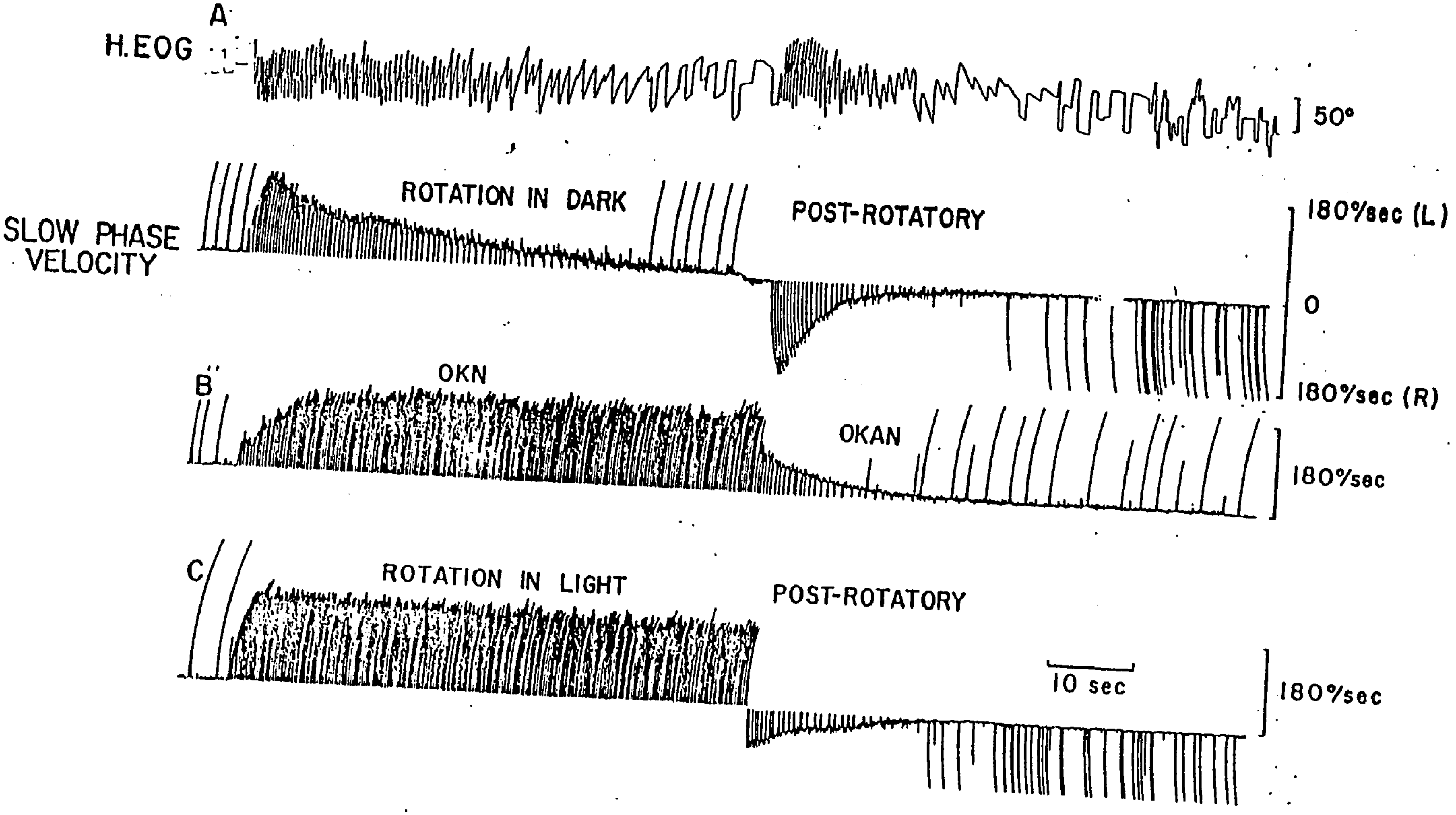

A
H. EOG
25°
SLOW PHASE VELOCITY
ROTATION IN DARK
POST-ROTATORY
60°/sec (L)
0
60°/sec (R)
B
OKN
OKAN
60°/sec
10 sec
C
ROTATION IN LIGHT
POST-ROTATORY
60°/sec

Figure 31. Characteristics of horizontal nystagmus at 180 deg/sec. Except for an increase in stimulus velocity, the traces are the same as in Figure 30. Note that OKAN has saturated (B), although the peak velocity of post rotatory nystagmus has not (A). Therefore, when the animal was stopped in darkness, post rotatory nystagmus appeared (C) that was only partially reduced by OKAN.


A
H.EOG
50°
SLOW PHASE VELOCITY
ROTATION IN DARK
POST-ROTATORY
180°/sec (L)
0
180°/sec (R)
B
OKN
OKAN
180°/sec
C
ROTATION IN LIGHT
POST-ROTATORY
10 sec
180°/sec

This was tested systematically using the experimental paradigm shown in in Figs. 32A, B.

This idea proved to be correct. Post rotatory upward nystagmus was weak after rotation that had induced downward vestibular nystagmus and OKN (Fig. 32A). In contrast, post rotatory downward nystagmus was strong after upward vestibular nystagmus and OKN were elicited (Fig. 32B). In Figs. 32C, D, the upward and downward peak post rotatory nystagmus velocity after rotation in darkness are shown by the triangles. They increased linearly with stimulus velocity to 180 deg/sec, with a response gain of about 0.98. Thus the strength of the post rotatory upward and downward nystagmus was the same. The post rotatory responses after rotation in light were quite different; however. After downward per rotatory nystagmus in light the upward post rotatory nystagmus was suppressed or greatly reduced for stimulus velocities up to 60 deg/sec (Fig. 32C, circles). Above this velocity slow phase velocity of the post rotatory responses increased with increasing stimulus velocities with a gain of about 0.95. In contrast in the same animal after upward rotation in light there was no measurable attenuation of the post rotatory response (Fig. 32D, circles). This shows that there had been no suppression or cancellation of the downward post rotatory rotatory nystagmus by preceding upward OKN.

Two other animals (991, 996) were tested for vertical visual vestibular interaction. The data are presented in Fig. 33. Post rotatory responses were almost entirely suppressed after rotations up to 60 deg/sec (Fig. 33B, C). Above this velocity, post rotatory nystagmus

Figure 32. Vertical visual-vestibular interaction. A and B are similar to Figures 30C and 31C. A shows downward rotation in light followed by a stop in darkness, and B shows upward rotation in light followed by a stop in darkness. Note that in A, upward post rotatory nystagmus is suppressed to some extent, whereas in B, downward post rotatory nystagmus is not suppressed. C and D show the relative degree of post rotatory suppression as a function of rotational velocity. Note that in C, upward post rotatory nystagmus after rotation in light (circles) is suppressed after rotations up to about 60 deg/sec. Post rotatory nystagmus after rotation in darkness (triangles) is shown to demonstrate the degree of suppression. Note also that above 60 deg/sec, the two responses have approximately the same gain. D shows that downward post rotatory nystagmus after rotation in light (circles) is not attenuated relative to post rotatory nystagmus after rotation in darkness (triangles).

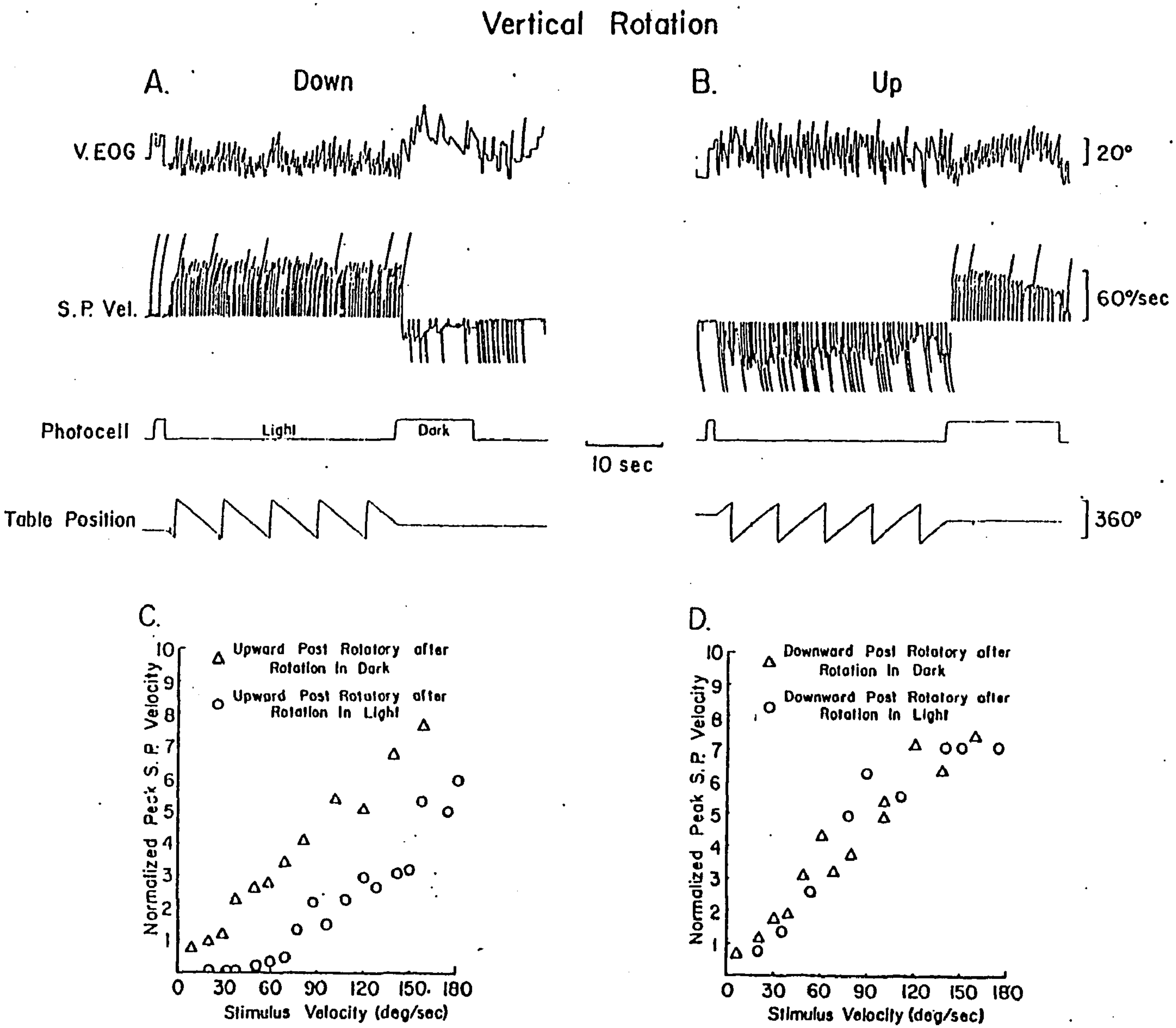
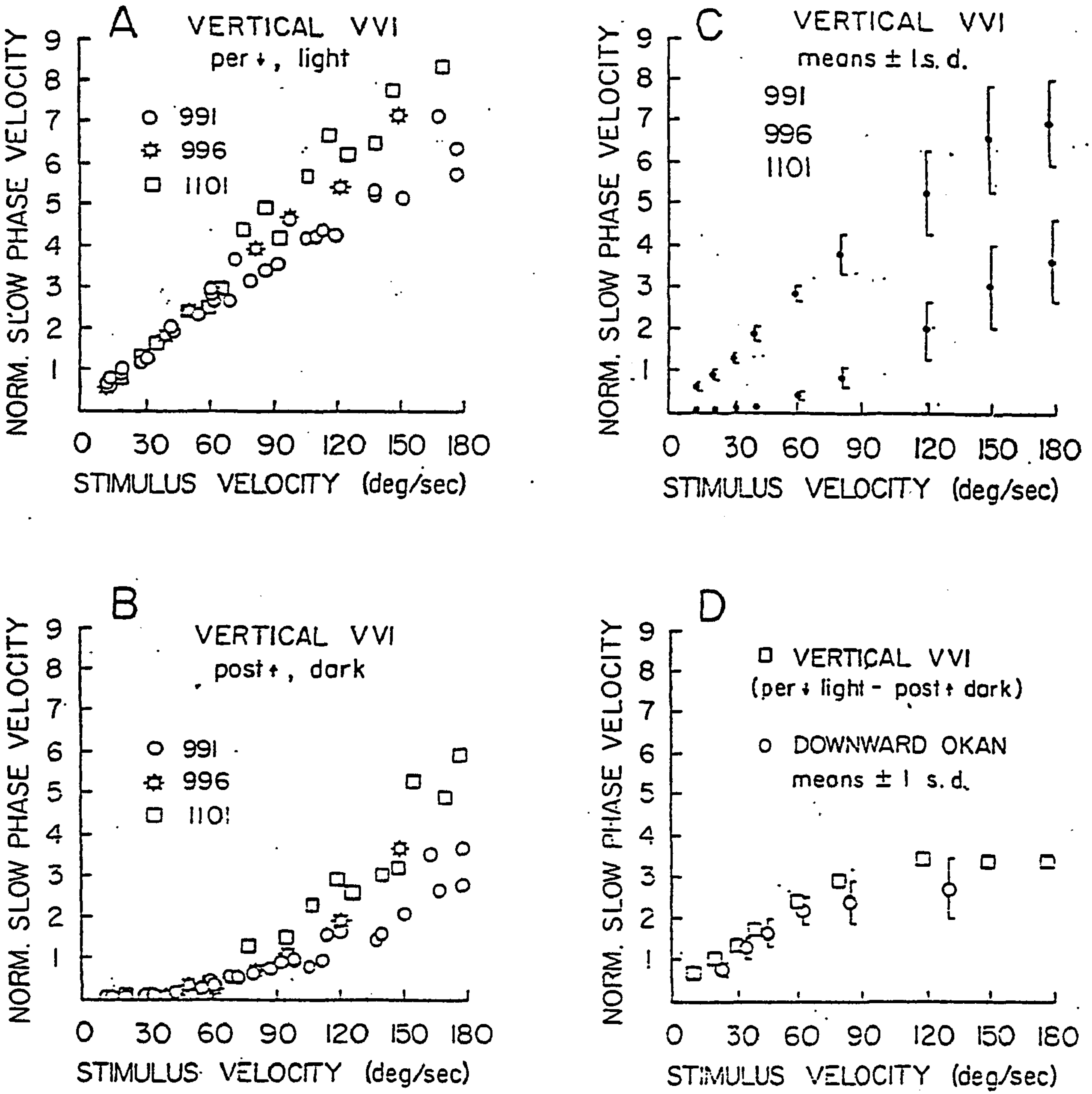

Vertical Rotation
A.
Down
B.
Up
V. EOG
S.P. Vel.
Photocell
Light
Dark
Table Position
10 sec
20°
60°/sec
360°
C.
Upward Post Rotatory after Rotation in Dark
Upward Post Rotatory after Rotation in Light
Normalized Peak S.P. Velocity
Stimulus Velocity (deg/sec)
0
30
60
90
120
150
180
1
2
3
4
5
6
7
8
9
10
D.
Downward Post Rotatory after Rotation in Dark
Downward Post Rotatory after Rotation in Light
Normalized Peak S.P. Velocity
Stimulus Velocity (deg/sec)

Figure 33. Effects of stored velocity on vertical visual-vestibular interaction. Separate plots of group data from downward per rotatory nystagmus in light (A) and the subsequent upward post rotatory nystagmus in darkness (B). Note that post rotatory responses are suppressed below 60 deg/sec. Means and standard deviations of the data in A and B are plotted together in C. The amount of nystagmus suppression was determined by subtracting post rotatory responses from per rotatory responses (squares, D). Group means and standard deviations (circles) are plotted on the same axes and overlay the derived data. This supports the idea that suppression of nystagmus at the end of rotation is due to the summation of stored velocity and post rotatory nystagmus.


A
VERTICAL VVI
per ↓, light
○ 991
✡ 996
□ 1101
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9
C
VERTICAL VVI
means ± 1 s.d.
991
996
1101
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9
B
VERTICAL VVI
post ↓, dark
○ 991
✡ 996
□ 1101
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9
D
□ VERTICAL VVI
(per ↓ light - post ↓ dark)
○ DOWNWARD OKAN
means ± 1 s.d.
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9

increased gradually to 180 deg/sec. The extent of suppression of the post rotatory upward responses was determined by subtracting the post rotatory upward response from upward per rotatory response. This is shown in Fig. 33D by the open squares. These values lay close to those for downward OKAN elicited by surround rotation at these same velocities (Fig. 33D, circles). This provides strong evidence for the hypothesis that OKAN that was induced during rotation in light had summed with and cancelled or reduced the oppositely directed post rotatory response. Similar data for horizontal nystagmus are shown in Fig. 34. In three animals there was a close correlation between reduction in post rotatory nystagmus after rotation in light and the amount of OKAN elicited by surround rotation at that velocity.

Three monkeys were rotated in light to evoke upward nystagmus (991, 996, 1101). Normalized peak slow phase velocities of upward per and post rotatory responses are shown in Fig. 35A, B. When the animals were stopped in darkness, downward post rotatory nystagmus resulted. The post rotatory responses recorded in darkness (Fig. 35C, triangles) was scarcely diminished relative to the per rotatory response after rotation in dark (circles). The degree of post rotatory suppression was measured by subtracting the mean peak post rotatory response from the mean peak per rotatory response. The results are shown by the open squares in Fig. 35D. These values were similar to the mean values of upward OKAN (circles). The correlation between lack of suppression of the post rotatory nystagmus and paucity of upward OKAN is evident. There was little or no reduction of the post rotatory response after upward rotation in light; neither was there significant upward OKAN following

Figure 34. Visual-vestibular interaction in horizontal nystagmus. A shows group data of horizontal rotation in light (upper curve) and the suppressed post rotatory nystagmus in darkness (lower curve). B shows the means and standard deviations of the data in A plotted versus rotational velocity. C shows the degree of suppressed nystagmus (squares) determined by subtracting post rotatory from per rotatory nystagmus. The group data of horizontal OKAN (circles) overlay the derived data, and indicate that in horizontal nystagmus as in vertical nystagmus, the suppression of nystagmus is due to the summation of post rotatory nystagmus with OKAN.

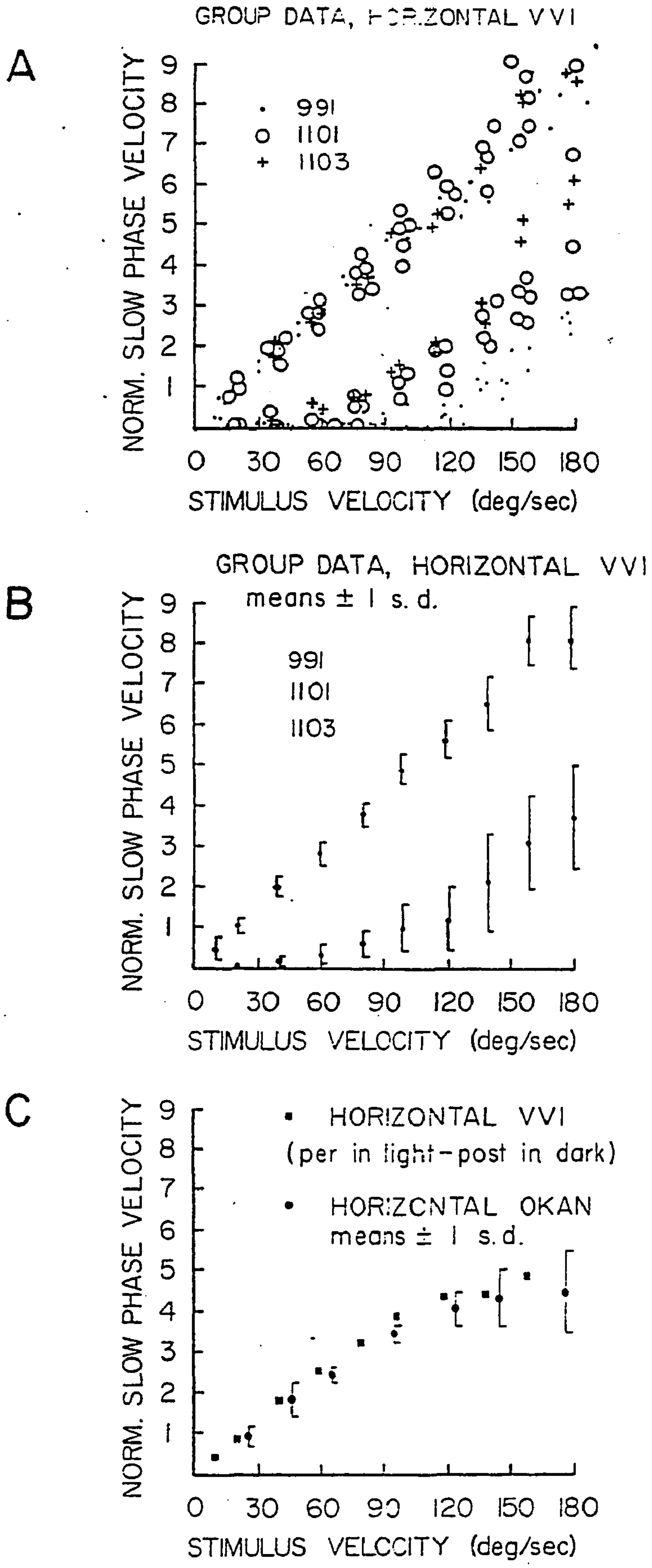
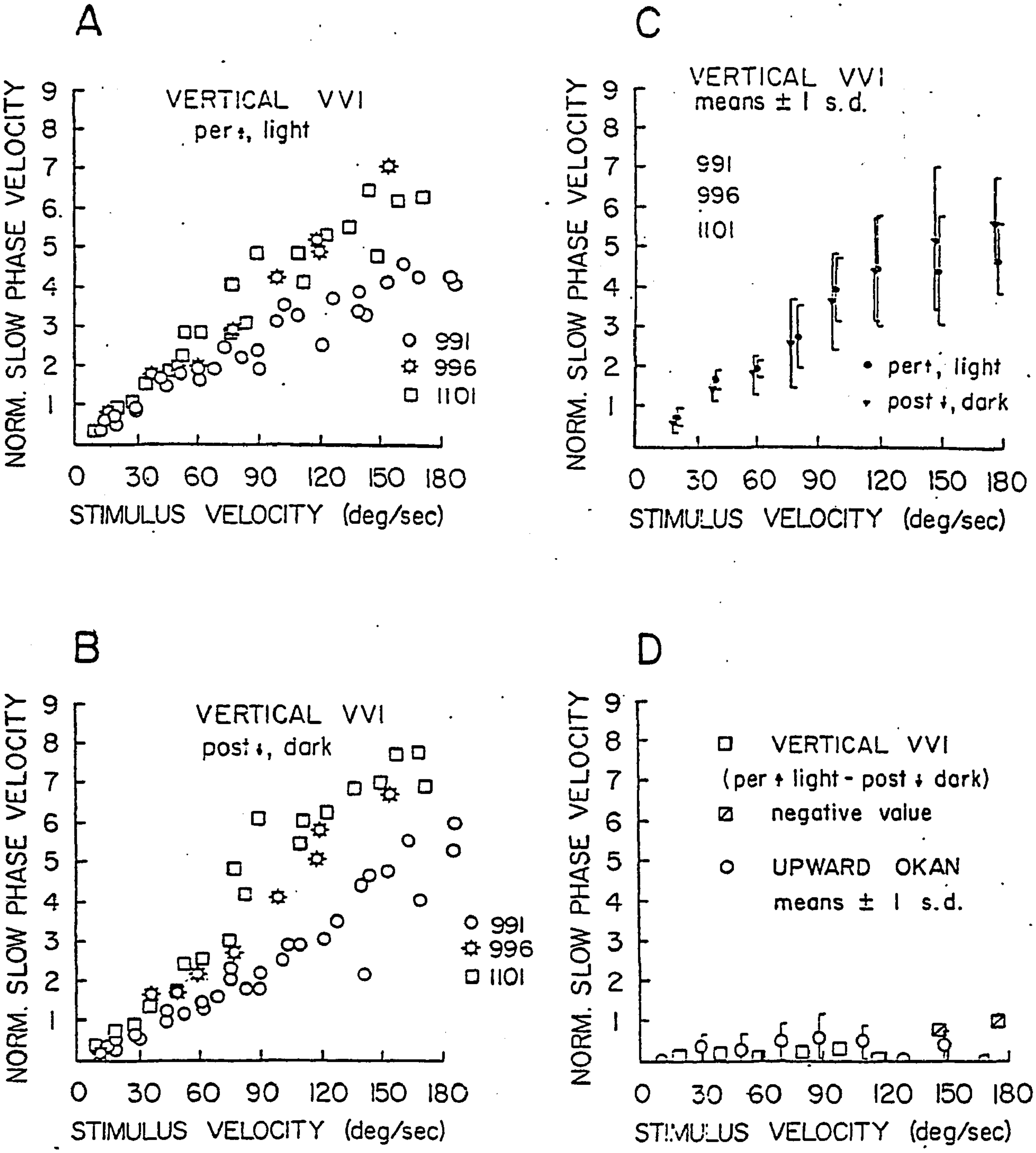

A
GROUP DATA, HORIZONTAL VVI
· 991
o 1101
+ 1103
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9
B
GROUP DATA, HORIZONTAL VVI
means ± 1 s. d.
991
1101
1103
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9
C
▪ HORIZONTAL VVI
(per in light-post in dark)
• HORIZONTAL OKAN
means ± 1 s.d.
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9

Figure 35. Vertical visual-vestibular interaction, upward rotation. A and B show the group per and post rotatory responses in light and darkness, respectively. Note that downward post rotatory nystagmus is not attenuated. C shows means and standard deviations of the data in A and B. Note that they are nearly superimposed. When post rotatory responses were subtracted from per rotatory responses (D, squares), virtually no suppression was evident. Occasionally post rotatory responses were greater than per rotatory responses (divided squares). Group means and standard deviations of upward OKAN (circles) are plotted on the same axes. The similarity of the data indicates that when there was no OKAN, post rotatory nystagmus was not suppressed.


A
VERTICAL VVI
per ↕, light
NORM. SLOW PHASE VELOCITY
STIMULUS VELOCITY (deg/sec)
0 30 60 90 120 150 180
1 2 3 4 5 6 7 8 9
○ 991
✡ 996
□ 1101
C
VERTICAL VVI
means ± 1 s.d.
991
996
1101
• per↕, light
▾ post ↕, dark
B
VERTICAL VVI
post ↕, dark
D
□ VERTICAL VVI
(per ↕ light - post ↕ dark)
▨ negative value
○ UPWARD OKAN
means ± 1 s.d.

drum rotations of 10 to 180 deg/sec.

It is possible to change the strength of the optokinetic contribution to visual vestibular interactions by moving the visual surround during platform rotation in light. If the surround moves in the direction opposite to the platform, the relative velocity between drum and platform is increased. If the surround moves in the same direction as the platform, the relative velocity between drum and surround is reduced or even reversed. In each of these situations the velocity of the eyes goes towards the relative velocity between the platform and optokinetic drum (Raphan et al., 1979). At the end of rotation, the amplitude and direction of the post rotatory response reflect the difference between the stored velocity induced by the optokinetic stimulus and the vestibular response provoked by the sudden stopping of the platform. Thus varying degrees of OKN can be elicited to summate with per rotatory eye velocities and effects on post stimulus nystagmus can be tested.

Examples of this experimental paradigm are shown in Fig. 36 for horizontal nystagmus. The after responses (marked by the arrows) varied according to the the vestibular post rotational velocity and the amount of OKAN induced by the relative velocity between the platform and the optokinetic drum. Data from a similar experiment are shown in Fig. 37. The baseline stimulus was a horizontal rotation in light at 45 deg/sec. When the animal was halted in darkness, post rotatory nystagmus was almost completely absent (cross hairs). OKN could be enhanced, reduced or suppressed entirely by rotating the drum in the opposite or same direction as the platform, respectively (solid line, open triangles).

Figure 36. Horizontal visual-vestibular interaction; effects of changing the visual input. A shows a 60 deg/sec rotation in light followed by a halt in darkness. At the end of stimulation there was about 10 deg/sec post rotatory nystagmus (arrow). When additional visual velocity was given, the per rotatory response increased and the post rotatory response was cancelled (B, arrow), or reversed (C,E). When the velocity of the visual input was decreased, the per rotatory response was diminished and the post rotatory nystagmus became more prominent (D,F, arrows).

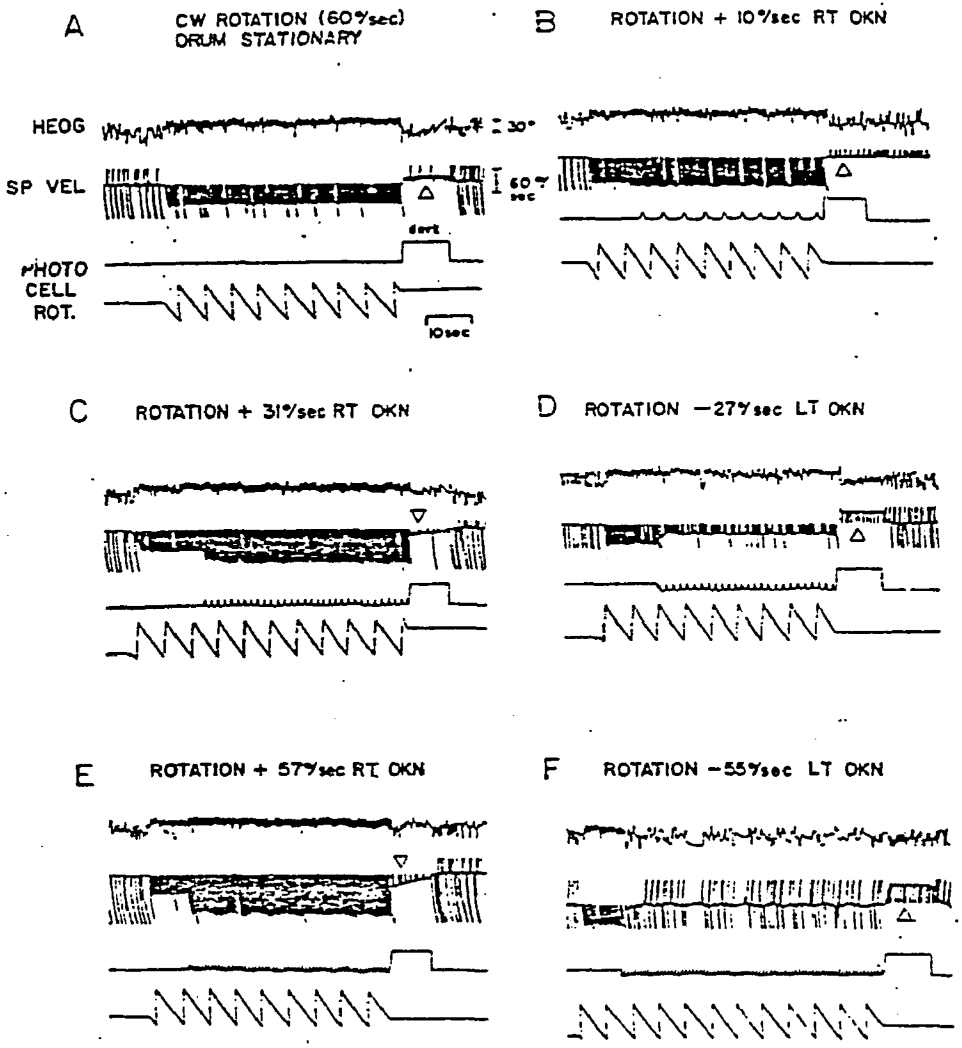

A
CW ROTATION (60°/sec)
DRUM STATIONARY
B
ROTATION + 10°/sec RT OKN
HEOG
SP VEL
PHOTO
CELL
ROT.
30°
60°/sec
dark
10 sec
C
ROTATION + 31°/sec RT OKN
D
ROTATION −27°/sec LT OKN
E
ROTATION + 57°/sec RT OKN
F
ROTATION −55°/sec LT OKN

Figure 37. Horizontal visual-vestibular interaction. Data from a similar experiment to the one in Figure 36 are shown. The platform velocity was 45 deg/sec. When the animal was halted in darkness, post rotatory nystagmus was nearly zero (cross hairs). Addition of optokinetic stimulation increased the velocity of the per rotatory response (open triangles, solid lines), and caused the post rotatory response (filled triangles, dashed lines) to appear in the same direction as OKAN. Conversely, rotating the drum in the opposite direction reduced the per rotatory nystagmus and caused the post rotatory response to appear in the direction of normal post rotatory nystagmus.

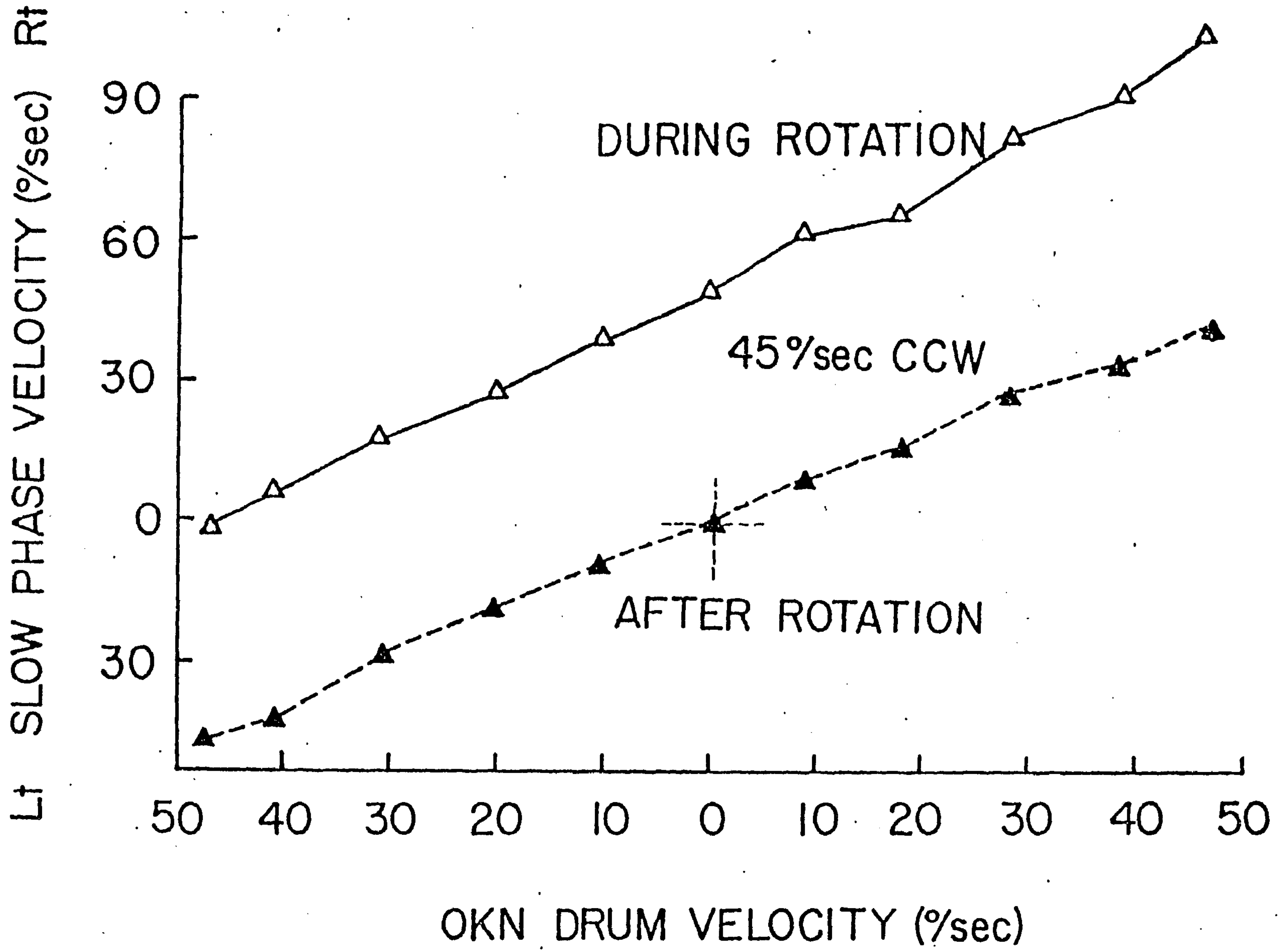
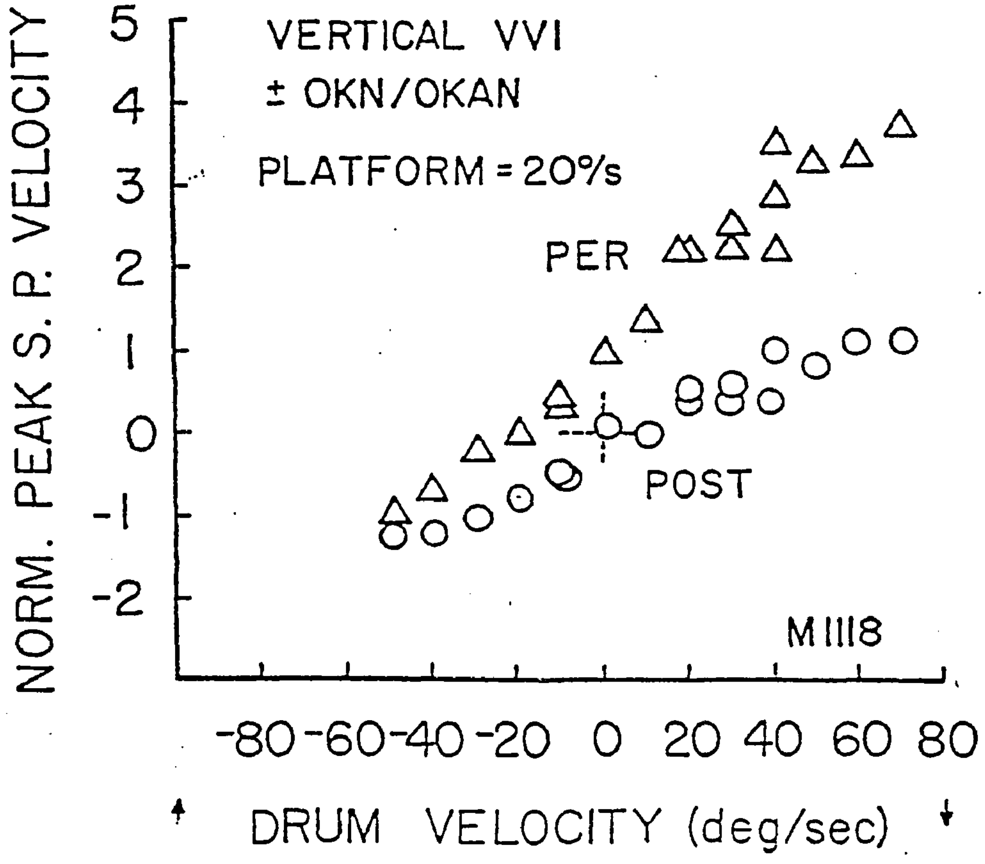

Rt
Lt
SLOW PHASE VELOCITY (°/sec)
90
60
30
0
30
DURING ROTATION
45°/sec CCW
AFTER ROTATION
50
40
30
20
10
0
10
20
30
40
50
OKN DRUM VELOCITY (°/sec)

Figure 38. Vertical visual-vestibular interaction; effects of changing the visual input. These data are similar to those in Figure 37, except that vertical nystagmus was tested. The platform velocity was 20 deg/sec, and upward and downward optokinetic stimuli were superimposed on the platform stimulus. The per rotatory response (triangles) was linearly modulated over the range of optokinetic stimuli that were used. Post rotatory responses (circles) were also modulated, but at a lower gain, reflecting the lower gain of vertical OKAN. The changes in post rotatory responses saturated at the extremes of the range of stimuli, reflecting the comparatively low saturation velocity of vertical OKAN.


VERTICAL VVI
± OKN/OKAN
PLATFORM = 20°/s
PER
POST
M1118
NORM. PEAK S. P. VELOCITY
5
4
3
2
1
0
-1
-2
-80 -60 -40 -20 0 20 40 60 80
DRUM VELOCITY (deg/sec)
↑
↓

The level of the post rotatory response was also modulated by changing the optokinetic input (dashed line, filled triangles). The slopes of the lines were parallel and separated by about 45 deg/sec. This indicates that stored velocity information was available to interact with post rotatory velocity over the range that was tested.

The same experimental paradigm was used to test vertical nystagmus. in a monkey (M 1118) that had about 10 deg/sec of upward OKAN. Downward nystagmus was induced by rotation in light at 20 deg/sec. The optokinetic drum was then rotated in the same or in the opposite direction at velocities up to 60 deg/sec. At the end of the velocity step the platform was braked, and the light was extinguished simultaneously. The experimental results are shown in Fig. 38.

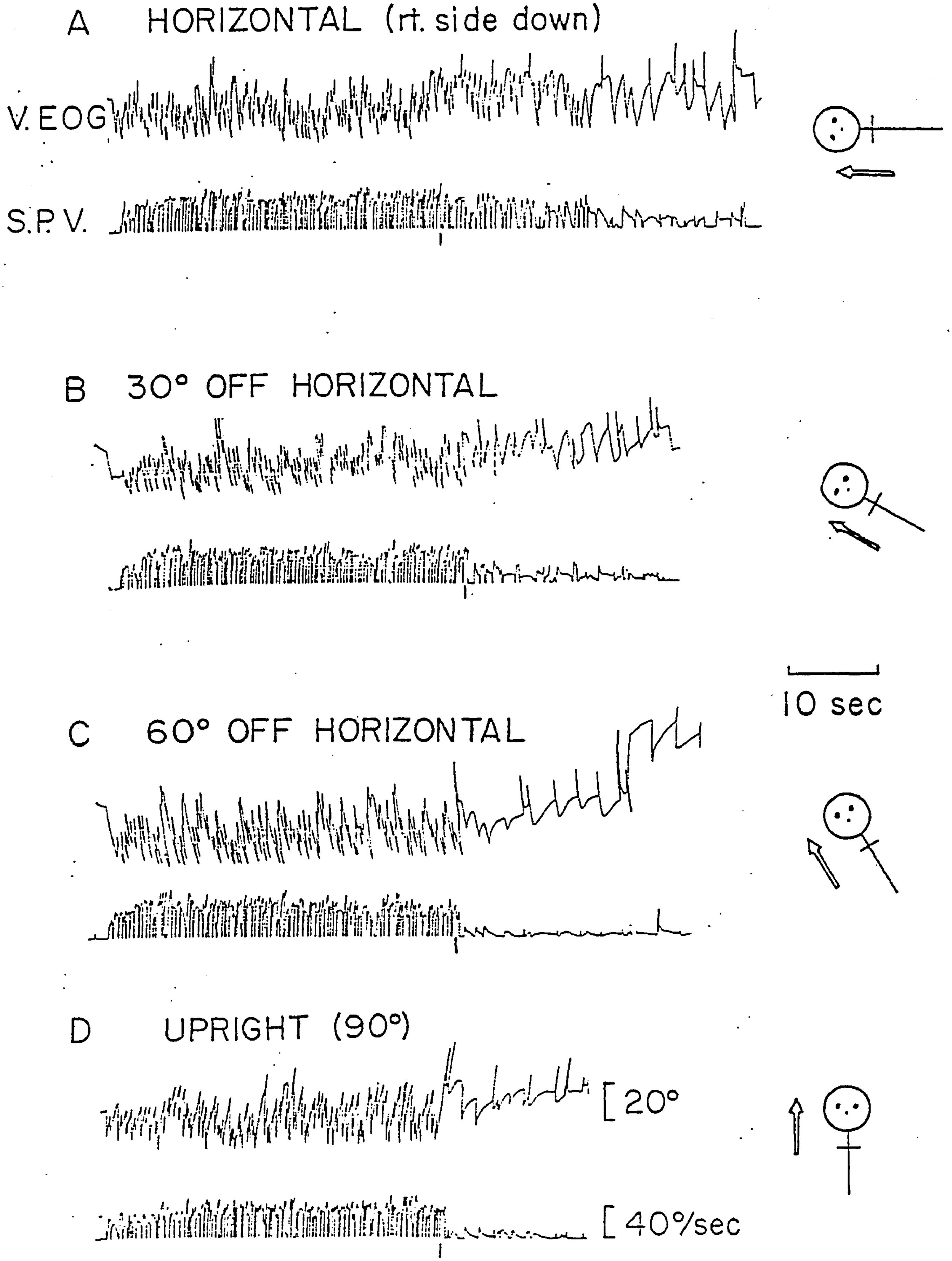
Drum rotations of -60 to -30 deg/sec reversed the nystagmus direction, since the drum was moving in the same direction as the animal but at higher velocities. This caused the eyes to beat upwards. Per rotatory responses are shown by the triangles. Drum rotations at -20 deg/sec suppressed the per rotatory nystagmus, since the drum was rotating in the same direction and at the same velocity as the platform, and the animal saw a stationary visual surround. Drum rotations of 20 to 60 deg/sec systematically increased slow phase velocities of downward per rotatory nystagmus. Thus per rotatory slow phase velocities were proportional to the relative velocity between the optokinetic stimulus and the platform velocity over the range of velocities that were tested.

Post rotatory responses in this stimulus paradigm are shown in Fig. 38 by the circles. When downward OKN was enhanced (positive values on the abscissa) downward nystagmus appeared in the post rotatory period, growing at a rate that closely approximated the slope of downward OKAN (circles to the right of the cross hairs). When downward OKN was decreased during rotatory responses (negative values on the abscissa), the amount of OKAN that could sum with and cancel the upward post rotatory response was also reduced. As a consequence the post rotatory response became stronger, rising to a peak value of about 20 deg/sec. Unlike the data in Fig. 37 whose slopes are parallel, the data in Fig. 38 converge. This is due to a saturation of the limited stored velocity activity available during upward OKAN to interact with the upward post rotatory response.

Effect of gravity on OKN and OKAN.

The effect of head tilt on OKN and OKAN was tested using equipment that recently became available. The animal was placed at angles of tilt in the roll axis from 0 (lateral position) to 90 degrees (upright) in 10 degree intervals and downward OKN was induced by full field rotation at 45 deg/sec. There were no apparent changes in steady state velocities of OKN (Fig. 39), but time constants of OKAN were affected. Time constants of downward OKAN are plotted versus angle of tilt in Figure 40. They were shortest when the animal was upright and longest when the animal was on its side. Although the results are not conclusive, they suggest that the time constant of vertical OKAN varies according to the angle of head tilt.

Figure 39. Effect of head tilt on vertical OKN and OKAN. Monkey 1118 was tilted in the roll axis at angles of zero to 90 degress and given full field optokinetic stimulation at 45 deg/sec. The stick figures show indicate the attitude of the animal, and the arrows indicate the direction of field movement. Note that OKN was unaffected, but OKAN time constants of decline were longest when the animal was on its side. Slow phase velocity traces are retouched.


A HORIZONTAL (rt. side down)
V. EOG
S.P.V.
B 30° OFF HORIZONTAL
10 sec
C 60° OFF HORIZONTAL
D UPRIGHT (90°)
[20°
[40°/sec

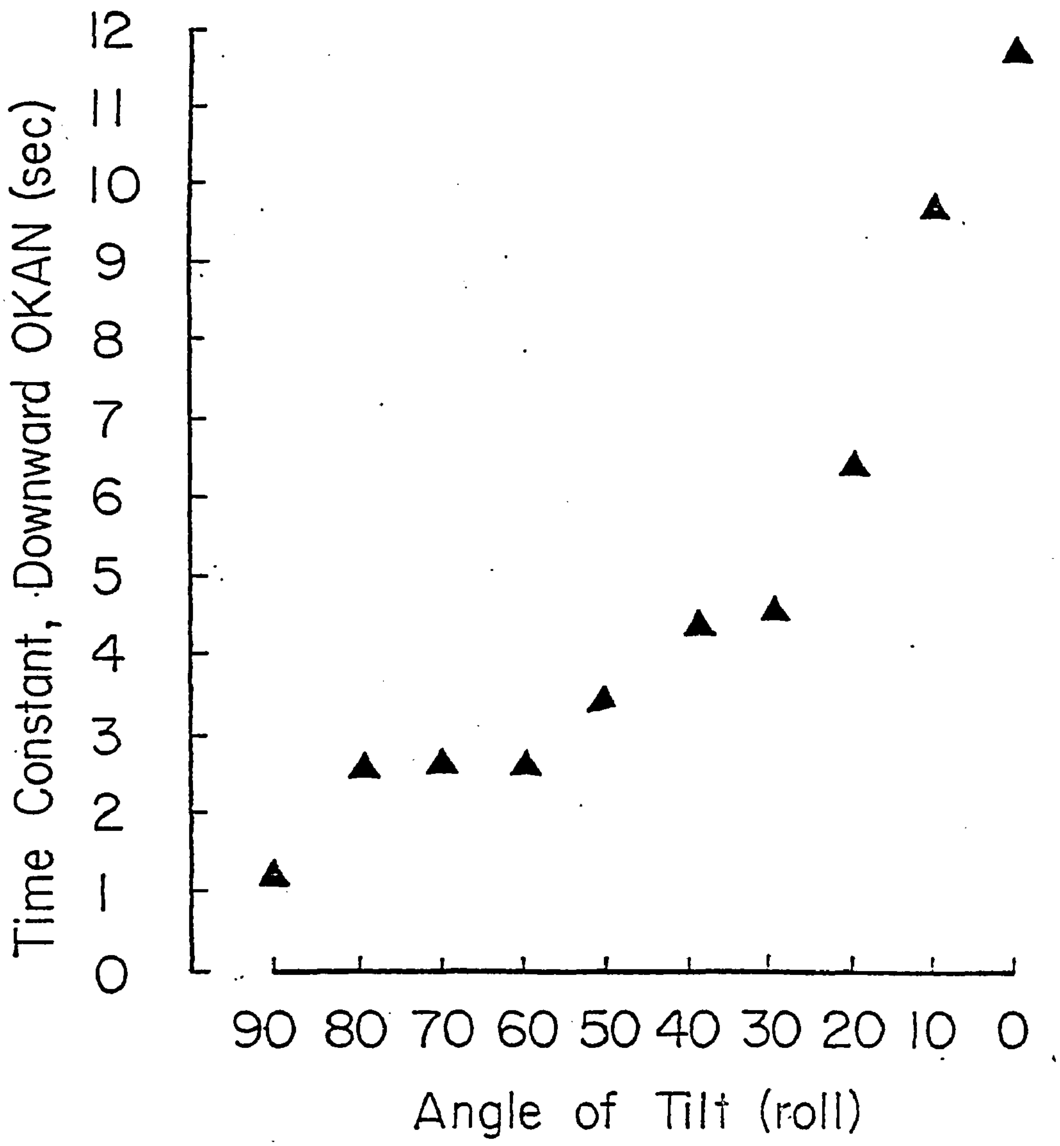


Figure 40. Effect of head tilt on time constant of vertical OKAN. Time constants of OKAN after a 45 deg/sec downward stimulus, are plotted as a function of head tilt in the roll axis. When the animal was upright (90 degrees), time constants were shortest. When the animal was on its side (0 degrees), the time constant was greatest, and in the range of time constants seen during OKAN testing.

IV. Discussion.

These experiments were undertaken to characterize vertical nystagmus and visual-vestibular interaction in the vertical plane. The results show that although horizontal nystagmus is left-right symmetrical, there are striking differences between upward and downward nystagmus. Upward OKN is weaker than downward OKN, upward OKAN is weak or absent, and upward vestibular nystagmus is of shorter duration and lower frequency than downward nystagmus. In addition, upward per rotatory nystagmus in light is irregular and is followed by strong downward post rotatory nystagmus. In contrast, downward per rotatory nystagmus in light is followed by weak upward post rotatory nystagmus. Post rotatory nystagmus could be increased, decreased or cancelled altogether by varying the relative velocity between the subject and the surround during downward nystagmus. Such modifications had no effect during upward nystagmus.

A number of models of the optokinetic response have appeared in recent years, beginning with the Collewijn (1972) analog simulation of the rabbit's optokinetic system. A review of current models for visual-vestibular interaction appears in Raphan and Cohen (1978) and Henn et al. (1980). The present results are discussed in the context of the Raphan model (Cohen et al., 1977; Raphan et al., 1977, 1979). In this scheme, horizontal OKN and OKAN, vestibular nystagmus and visual-vestibular interactions are modelled by assuming that there is cooperative interaction of direct visual and vestibular pathways, and a common indirect pathway that includes an integrator that stores activity related to slow phase eye velocity (Cohen et al., 1977; Raphan et al., 1977, 1979). The present results can be explained in the context of this organization if the gain of the direct visual-oculomotor pathways for downward slow phases or pursuit is low, and if there is little or no capacity for storing activity related to downward slow phase eye velocity during upward nystagmus.

OKN and OKAN.

There are a number of indications that stored activity related to slow phase velocity is weak or absent during upward OKN. OKN gain is low and slow phase velocities are irregular. There is a rapid rise during upward OKN at the onset of stimulation, but generally no subsequent gradual rise in slow phase velocity to a steady state level. At the end of stimulation there is usually no upward OKAN. However, when upward OKAN is present, a gradual rise in OKN is also seen, although the responses have a much lower gain than downward OKN, (Fig. 18C).

The characteristics of upward OKN, which in normal animals is essentially produced without a contribution of stored velocity information, are seen in horizontal OKN of animals after bilateral labyrinthectomy (Uemura and Cohen, 1973; Collewijn, 1976). Tonic activity from the vestibular end organ appears to be essential for maintaining the velocity storage mechanism. After labyrinthectomy the velocity storage integrator appears to be disabled and OKAN is no longer produced. As a result there is only a rapid, not a slow rise in OKN, and OKN slow phase velocities are irregular and only have a gain of about 0.6. The absence of storage for upward nystagmus is not due to an absence of tonic activity in posterior or anterior canal nerves, so that if a neural integrator for upward nystagmus exists at all, either it cannot be charged to a high velocity or coupling to it from the visual and vestibular systems must be weak.

If velocity storage for upward nystagmus is minimal, then upward OKN is probably produced mainly by activation of direct visual-oculomotor pathways. This implies that at least part of the difference in the rapid rise in velocity at the onset of upward and downward OKN is due to a difference in gain of the direct pathways in these animals. There are no studies that have directly tested this postulate but there is fragmentary evidence that pursuit in downward and upward directions may be asymmetrical in monkeys. The rapid rise in OKN reaches higher levels at the onset of downward than upward OKN (Figs. 8, 10, 18). Visual suppression of nystagmus has been postulated to be sum of the pursuit signal in the direct visual pathways with the signal generated in the VOR (Lisberger and Fuchs, 1974; Robinson, 1975). During visual suppression of downward nystagmus, a retinal slip signal in the opposite direction is generated by the velocity of the eyes in light. If the animals had a lower pursuit gain for downward than upward retinal slip, i.e., for slow movements in the downward than the upward direction, they would be expected to have difficulty in suppressing downward nystagmus in light due to poor visual following of the relative downward field motion. It was a general finding that the animals had greater ability to visually suppress upward than downward vestibular nystagmus.

Asymmetry in pursuit gain in the vertical plane has been reported in other species including cats and humans. In trained cats optokinetically-assisted upward pursuit reached higher velocities than downward pursuit (6 deg/sec vs 2.5 deg/sec, respectively) (Evinger and Fuchs, 1978). These animals also have an asymmetry in vertical OKN with upward OKN being weaker than downward OKN (Collins et al., 1970; Vital-Durand and Jeannerod, 1974).

In humans there is controversy as to whether vertical optokinetic responses are symmetrical. Horizontal OKN in humans is largely composed of pursuit, and stored velocity information makes a relatively small contribution to it (Cohen et al., 1981). Stiefel and Smith (1962) used a small hand-held optokinetic drum to elicit vertical OKN, and measured nystagmus frequency. They suggested that upward nystagmus was somewhat more vigorous, but Dubois and Collewijn (1979b) found symmetrical open and closed loop gains of the vertical optokinetic response of humans. Their stimulus field was restricted to 10 degrees and the stimulus velocities were low, ranging from 0.016 to 16 deg/sec. Collins et al. (1970) used a full-field stimulus moving at 24 deg/sec. They also reported no significant directional asymmetry of vertical OKN. However, Takahashi et al., (1978) found that humans had higher slow phase velocities of downward OKN than upward OKN, but they used a wide field optokinetic stimulus and stimulus velocities above 50 deg/sec. Thus, at lower velocities and smaller field sizes, upward and downward OKN and/or pursuit may be equal in humans, but at higher velocities asymmetries are present, similar to those found in monkeys. Humans also have poorer suppression of downward than upward nystagmus (Guedry, 1970; Guedry and Benson, 1970; Benson and Guedry, 1971; Guedry and Benson, 1971; Barnes et al., 1978). If a pursuit velocity is used to suppress the VOR, this is consistent with the idea that the subjects had asymmetry in vertical pursuit.

Storage of activity related to slow phase velocity is not only an important determinant of the characteristics of OKN, OKAN, vestibular nystagmus and visual vestibular interactions but it also serves as the focus for adaptive gain changes of the VOR. Lisberger, Miles, Optican and Eighmy (1980) have recently shown that when the gain of the monkey's VOR was plastically adapted by either raising or lowering it, the rapid rise at the onset of OKN did not change. Rather, the change in VOR gain was directly related to the amount of stored activity, as manifested in the saturation level of OKAN. During optokinetic testing in such animals, if VOR gain was increased, the gain of the slow rise of steady state OKN, and the peak velocity of OKAN increased, and vice versa. The gain of the rapid rise was markedly lowered by flocculectomy. After flocculectomy, the gain of the slow rise of OKN was unchanged, although the charging time constant increased (Optican, Zee, Miles and Lisberger, 1980). This suggests that when the gain of the direct pathway is reduced, the velocity storage integrator can support constant velocity following, up to the saturation level of OKAN. Conversely, if the velocity storage mechanism is absent and the gain of the direct visual oculomotor pathways is low, slow phase velocities of OKN are irregular and have a low gain. This is consistent with the idea stated above, that the characteristics of upward OKN are probably the result of a low gain in the direct pathways as well as the absence of stored velocity.

Stored velocity may also be related to the perception of motion, and to Coriolis and pseudo-Coriolis effects that occur during horizontal OKN and vestibular stimulation (Brandt and Dichgans, 1972; Dichgans and Brandt, 1972; Brandt, Dichgans and Koenig, 1973; Dichgans and Brandt, 1973; Brandt, Dichgans and Buchele, 1974). In humans, circular vection develops during OKN over approximately the same time course as stored velocity did in the present study, and the sensation of circular vection outlasts the optokinetic stimulus by about 10 sec. The sensation of rotation after velocity steps in darkness also parallels the time course of post rotatory nystagmus (Guedry et al., 1961). During visual suppression of vestibular nystagmus, circular vection was permanently reduced, although there was recovery of nystagmus when the subjects were in darkness again (Guedry et al., 1961; Cohen et al., 1981). It is not clear whether there is a similar relationship between stored velocity and motion perception during vertical nystagmus. If velocity storage is also related to circular vection in the vertical plane, one would expect that downward apparent body motion corresponding to downward OKN should be strong, and persist after the end of stimulation, whereas upward vection might be more difficult to induce, and would not persist after the end of stimulation. Young, Oman and Dichgans (1975) tested the sensation of static head tilt induced by upward and downward full field optokinetic stimuli. The sensation of pitching down, corresponding to upward field motion and downward nystagmus, was much stronger than the sensation of pitching up during an equal but oppositely directed movement of the field.

Vestibular nystagmus.

Peak velocities of horizontal and vertical vestibular nystagmus gains were near unity over a wide range of stimuli, and peak velocities in either direction were symmetrical. This is probably because the peak velocities of vestibular nystagmus are determined by the activity in the vestibular nerve and the direct vestibular pathways. Goldberg and Fernandez (1971) and Fernandez and Goldberg (1971) have shown that the activity in the vestibular nerve, which presumably reflects the deflection of the cupula, is essentially symmetrical, in the range of velocities used in this study. This indicates that differences in time constants of vertical nystagmus were not due to differences in end organ activity.

Characteristics of horizontal and downward nystagmus were comparable. In contrast, durations of upward vestibular nystagmus was shorter than either downward or horizontal nystagmus. Similar directional asymmetries were reported by Mygind (1925), Money and Scott (1962), Guedry and Benson (1970) and Koempf et al. (1979). Since the asymmetry in vertical nystagmus is not due to an asymmetrical response of the labyrinth or to an inability to move the eyes rapidly downward during slow phases of nystagmus, it is more likely to be a sign of differences in the central neural organization of vertical nystagmus. Time constants for upward nystagmus were frequently around 5 sec, the time constant of canal related activity in the vestibular nerve. This indicates that neuronal signals related to upward vestibular nystagmus reached the eye muscle motoneurons without much further processing by the velocity storage integrator. This is consistent with the idea that upward vestibular nystagmus is predominantly determined by direct pathways around the integrator.

As noted above, the influence of the direct visual pathways is seen in the rapid drop of slow phase velocity during visual suppression. Declines of slow phase velocity during visual suppression of vertical nystagmus could be either gradual or abrupt, suggesting variability in the effectiveness of the direct pathways to suppress vertical nystagmus. Fixation suppression of downward vestibular nystagmus required longer fixation periods than did horizontal or upward nystagmus. This is consistent with findings of psychophysical investigations in humans. Subjects who had to suppress vertical nystagmus so that they could read a display were less able to do so during downward nystagmus than during horizontal or upward nystagmus (Guedry, 1970; Guedry and Benson, 1970; Benson and Guedry, 1971; Guedry and Benson, 1971; Barnes et al., 1978).

Visual-vestibular interaction.

The scheme for the summation of activity for vestibular and optokinetic nystagmus was first suggested by Ter Braak (1936) and Mowrer (1934, 1937). It was formalized in a model presented by Raphan et al. (1977, 1979). A similar model was also formulated by Robinson (1977). The key feature in each instance is that activity stored during OKN interacts with vestibular activity to cancel or reduce the post rotatory response; the after response is the sum of the peak velocity of OKAN and post rotatory nystagmus. After rotation in a stationary lighted environment, the responses are nearly equal and in opposite directions. As a result, the after response is frequently near zero. However it is theoretically biased slightly in favor of the post rotatory response, since the gain of the direct vestibular pathway is near unity but the gain of the stored OKN velocity is only 0.6 to 0.85. As a result, post rotatory nystagmus usually occurs after rotation in light. However, as shown in Fig. 36 A,B, it can be cancelled by increasing the velocity of the optokinetic input. The finding that the amount of velocity storage could be manipulated by adding or subtracting optokinetic velocity, which in turn changed the post rotatory responses is strong support for the idea of summation. As anticipated, velocity storage was weak or absent during upward nystagmus and there was no cancellation of the downward post rotatory response.

Functional significance of the asymmetry.

Several explanations of the asymmetry in vertical nystagmus have appeared. Igarashi et al. (1978) have suggested that due to the "peripheral ocular anatomy", upward OKN is less easily provoked than downward OKN. Peak gains of upward and downward vestibular nystagmus were approximately equal, although the peak velocity of downward slow phases was sustained for only a very brief time. Therefore it is unlikely that the anatomy of the eye is responsible for the differences in slow phase velocities of vestibular nystagmus and OKN that were noted. Benson and Guedry (1971) have suggested that the directional asymmetry may serve to prevent or reduce nystagmus evoked by downward moving visual stimuli when walking forward, and is a product of training or evolution (Guedry and Benson, 1971). This suggests that the constant movement of the environment in the lower visual field that occurs when man and animals move forward, has produced a highly adapted upward OKAN with little velocity storage. Consistent with this notion, Dubois and Collewijn (1979a) reported a marked asymmetry in horizontal nystagmus in the rabbit. This animal, which is lateral eyed, has poor anterior beating nystagmus and strong posterior beating nystagmus. It is possible that the directional asymmetry has provided some unspecified evolutionary advantage. In any event, it is clear that a satisfactory explantation for the directional asymmetry in vertical nystagmus has yet to appear.

Effects of gravity on the vertical VOR.

Under natural circumstances, stimuli that evoke nystagmus must involve a complex interaction of inputs from not only the visual receptors and the semicircular canals, but also from the otoliths and possibly cervical, somatosensory and visceral receptors. Recently, it has been shown that the otoliths respond to a gravity vector rotating with regard to the head and have a powerful effect on inducing horizontal nystagmus from the VOR (Raphan et al., 1981). Gravity has also been shown to have a significant influence on the direction and frequency of flicker-induced nystagmus in monkeys (Pasik, Valciukas and Pasik, 1973). Flicker induced nystagmus and flicker induced after nystagmus have characteristics that suggest that they may be mediated by a similar integrator utilizing vestibular activity (Pasik, Pasik and Valciukas, 1970; Pasik et al., 1973; Pasik and Pasik, 1975; Miller, Pasik and Pasik, 1979).

It is probable that vertical nystagmus also is affected by changes in head attitude with regard to gravity. Benson and Guedry (1971) found that subjects became quite ill when they were rotated in the lateral position, exciting the vertical canals without activating the otoliths. This was not the case when the same subjects were rotated in an upright position around an earth-vertical axis. The position of the head during vertical OKN may have modulated the effectiveness of environmental motion. Consistent with this, Young et al. (1975) reported that the sensation of pitching during vertical optokinetic stimulation was strongly affected by changes in head position. When the head was tilted 25 degrees forward, pitch sensations were markedly reduced and only a sensation of linear vection was reported. This effect may reflect the saturation level of pitching sensation, however, since the mean pitch angle evoked by optokinetic stimuli with the head erect did not exceed 25 to 30 degrees. When subjects were tested in the lateral position, the pitching sensation was markedly enhanced. Young et al. (1975) attributed the effectiveness of head position on changing pitch sensation to a sensory conflict between visual stimuli associated with vertical movement and a lack of confirming otolith input. With the head in the lateral position, the utricles were in the least sensitive position with respect to changes in body position and subjects were least able to suppress the sensation of pitch. When the head was tilted

25 degrees forward, the utricular maculae were nearly horizontal and subjects could suppress the sensation of pitching, but not linear vection. Thus, testing our animals in the lateral position may have fortuitously revealed the maximum amount of stored velocity in the vertical plane.

Full field visual stimulation usually occurs with head movement. There is ordinarily a change in attitude with regard to gravity during vertical head movements that does not usually occur during head movements in the horizontal plane. Therefore, it might be expected that the otolith organs would have an effect on the vertical VOR and velocity storage that would be different from any such effect on horizontal nystagmus. There is some experimental evidence to support this idea. Barmack (in press) reported that during low frequency sinusoidal rotation, the gain and phase characteristics of the vertical VOR in rabbits were improved when the otoliths and semicircular canals acted synergistically. Igarashi et al., (1978) severed the utricular nerves and destroyed the saccular maculae bilaterally. This enhanced slow phase velocities of vertical OKN in both directions. Following destruction of the otolith organs slow phase velocities of downward OKN were about the same as those in the present report, and slow phase velocities of upward OKN were higher than those described here. Igarashi et al., (1978) also found that with the maculae gone, downward OKAN was stronger and lasted longer, although upward OKAN was not affected. Horizontal OKN and OKAN were not affected by otolith ablation (Takahashi et al., 1977).

In the present results there were no systematic differences in steady state vertical OKN velocity with the animal tilted at angles of 0 to 90 deg, although OKAN was affected. The time constants of decay varied between these two positional extremes as a function of the angle of tilt. This supports the notion that gravitational forces have an important influence in modulating vertical nystagmus.

Summary.

The purpose of this research was to determine the degree of velocity storage during vertical nystagmus in monkeys. The results were compared to storage during horizontal nystagmus. Unlike horizontal nystagmus which was bilaterally symmetrical, vertical nystagmus was asymmetrical. There was more velocity storage during downward nystagmus than during upward nystagmus. This was seen in the following characteristics of vertical nystagmus.

1. Downward OKN slow phase velocity increased in proportion to stimulus veocity with a gain of 0.90 to 0.96, for stimulus velocities of up to 60 deg/sec. Upward OKN gain was 0.6 to 0.7 for the same stimulus range.

2. Downward OKAN slow phase velocities increased following increases in optokinetic stimulus velocities to 60 deg/sec, with a gain of about 0.7. OKAN slow phase velocity saturated at about 45 deg/sec. Upward OKAN was not always elicited, and when it was present it had low peak velocities and was usually brief. Regardless of the preceding stimulus or optokinetic velocity, peak velocities of upward OKAN seldom exceeded 10

to 20 deg/sec. Time constants of downward OKAN were 10 to 20 sec, whereas time constants of upward OKAN were too short to be measured accurately with the techniques employed in this study.

3. Gains of upward and downward vestibular nystagmus in response to steps of velocity were approximately equal, but time constants of decline of downward vestibular nystagmus always exceeded those of upward nystagmus. Downward vestibular time constants ranged from 12 to 16 sec, whereas upward time constants ranged from 5 to 10 sec.

4. Asymmetrical storage of activity related to slow phase velocity was also present in vertical visual-vestibular interactions. The presence or absence of stored velocity information was reflected in the after responses following vestibular velocity steps in light. The presence of downward OKAN cancelled or reduced upward post rotatory responses in darkness, while weak upward OKAN had scarcely any effect on downward post rotatory responses.

5. The charging time constants of downward OKN and OKAN were estimated to be 3.5 to 3.7 sec, using a technique described in Cohen et al. (1977). An animal with some upward OKAN was tested in this series. The time constants of rise of upward OKN and OKAN were in the same range, viz., 3.4 and 3.7 sec, respectively. The steady state levels reached during upward nystagmus were always considerably lower than those reached during downward nystagmus.

6. Visual suppression was compared during upward and downward vestibular nystagmus. Again a clear asymmetry was demonstrated. Downward nystagmus was more persistent during and after visual suppression than upward nystagmus was. The time constant of decline of downward vestibular nystagmus after visual suppression was 7 to 8 sec. The time constant of decline of upward vestibular nystagmus after visual suppression of nystagmus was about 3.5 sec. The time constant of visual suppression of downward OKAN was 3 to 4 sec.

The results are summarized in Table 2. They were interpreted within the framework of a model of optokinetic and vestibular nystagmus generation developed by Raphan (Cohen et al., 1977; Raphan et al., 1977, 1979). In this model, optokinetic and vestibular nystagmus are the result of combining "direct" visual and vestibular pathways that respond quickly to changes in environmental or head velocity, and "indirect" pathways that go through a neural integrator that is responsible for storage of activity related to slow phase velocity. The velocity storage integrator serves to regularize slow phase velocities during OKN and to improve the low frequency characteristics of the vestibular system. The asymmetry in vertical nystagmus was explained in terms of the model by proposing that the direct visual oculomotor pathways, which may subserve pursuit, have lower gains for downward than for upward nystagmus. Further, the velocity storage integrator is strongly activated during downward optokinetic and vestibular nystagmus but weakly or not at all during upward nystagmus. The asymmetry was not due to an inability to move the eyes downward at high velocities but rather

TABLE 2

	Unity Gain	Saturation Velocity	Frequency (b/s)	Charge TC
H OKN	120 deg/sec	140-160 deg/sec	1.8-3.3	2.6-3.3 sec
V OKN (down)	60 deg/sec	80 deg/sec	2.3-4.2	3.5 sec
V OKN (up)	20 deg/sec	50 deg/sec	1.3-2.3	3.5 sec

	Saturation Velocity	Gain	Time Constant of Decline	Time Constant Visual Suppression
H OKAN	70-90 deg/sec	0.85	5-20 sec	1-1.4 sec
V OKAN (down)	45 deg/sec	0.6-0.7	10-20 sec	3-4 sec
V OKAN (up)	10 deg/sec	0.2		
H VOR			12-28 sec	3 sec
V VOR (down)			12-16	7-8 sec
V VOR (up)			5*-10 sec	3.5 sec

could be attributed to an inability of central neuronal mechanisms that control vertical eye movements to maintain high levels of downward eye velocities. The functional significance of this asymmetry is unknown.

Suggestions for future research.

1. A parametric study of the effect of head position on velocity storage would provide clues to the participation of graviception on the VOR. In the present study, only changes in the roll axis were made, over a 90 degree range, and only one optokinetic velocity was tested. It would be interesting if, through some manipulation of the otoliths, upward velocity storage could be improved.

2. Lesions that selectively disrupt horizontal or vertical storage would provide evidence for whether there was more than one integrator, i.e., one for horizontal nystagmus and one for vertical nystagmus. It is possible that there are more than two velocity storage mechanisms, viz., one for each direction of horizontal and vertical nystagmus. One such lesion would be the selective section of the horizontal canal nerves. This would probably disrupt horizontal velocity storage. If vertical velocity storage were left intact, it would imply a separate storage mechanism for the two planes.

3. Fixation suppression has been shown to be affected by flocculectomy. So far the suppression has only been tested for horizontal nystagmus. There is a topographical arrangement of eye movements in the flocculus,

where stimulation of rostral or caudal portions of the flocculus produced horizontal or vertical eye movements, respectively (Dufosse, Ito and Miyashita, 1977). Fixation suppression of vertical nystagmus before and after flocculectomy has not been reported.

4. Unit recordings of neurons in the vestibular nuclei show that these neurons have activity related to stored velocity in one plane. So far, only the horizontal plane has been extensively tested. Units that responded to horizontal head movements or environmental movements did not respond to movements in the plane of the vertical canals. The location and characteristics of vertical movement sensitive neurons that show evidence of stored activity in the vestibular nuclei or elsewhere would be important to know.

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