

## **Nystagmus Slow-Phase Velocity During Vestibular, Optokinetic, and Combined Stimulation in the Monkey**

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**Summary.** In Rhesus monkeys the slow-phase velocity of nystagmus was measured during optokinetic, vestibular, and combined stimulation. Accelerations and decelerations of  $2.5\text{--}40^\circ/\text{s}^2$ , and rotation at constant velocities of  $70\text{--}160^\circ/\text{s}$  were applied. During combined visual-vestibular stimulation, nystagmus slow-phase velocity is a function only of the instantaneous stimulus velocity: It has a gain near unity and is independent of the duration and value of the acceleration. The limited linear working range of the vestibular or optokinetic system is thus extended. During deceleration an inappropriate nystagmus response is elicited only when the previous constant velocity rotation was above the saturation velocity of optokinetic nystagmus (OKN). These results are related to single neuron activity recorded in the vestibular nuclei and the flocculus under identical stimulus conditions.

**Key words:** Optokinetic nystagmus – Vestibular nystagmus – Visual-vestibular interaction – Monkey.

**Zusammenfassung.** Bei Rhesusaffen wurde die Geschwindigkeit der langsamen Phase des vestibulären Nystagmus (VN), optokinetischen Nystagmus (OKN) und des kombinierten Nystagmus (VN + OKN) während rampenförmiger Stimulation untersucht.

Be- und Entschleunigungswerte variierten zwischen  $2,5$  und  $40^\circ/\text{s}^2$ , Endgeschwindigkeiten konstanter Drehung zwischen  $70$  und  $160^\circ/\text{s}$ . Während der Beschleunigung ist die Nystagmusgeschwindigkeit bei kombinierter Stimulation proportional zur momentanen Geschwindigkeit, unabhängig vom Beschleunigungswert. Der lineare Arbeitsbereich des vestibulären und optokinetischen Systems wird dadurch stark erweitert. Bei der Entschleunigung tritt nur dann ein nicht reizadäquater Nystagmus auf, wenn die vorangehende Rotation mit konstanter Geschwindigkeit über der Sättigung des OKN lag. Die

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Resultate weisen auf eine enge Beziehung zwischen Nystagmus und neuronaler Aktivität im vestibulären Kern und Flocculus hin.

**Schlüsselwörter:** Optokinetischer Nystagmus – Vestibulärer Nystagmus – Visuell-vestibuläre Interaktion – Affe

## Introduction

Optokinetic and vestibular stimulation can both induce nystagmus. The response in each case serves to stabilize vision, and ideally the slow-phase velocity of the nystagmus should match the stimulus velocity. In that case, the gain of the nystagmus is said to be unity, and nystagmus is said to be compensatory. In this paper we will describe the optokinetic nystagmus (OKN) and vestibular nystagmus (VN) slow-phase velocity in Rhesus monkeys in response to different values of angular acceleration and constant velocity rotation of the monkey or its visual surround. We shall then examine how these responses interact during combined optokinetic-vestibular stimulation. It is known that responses to pure optokinetic or vestibular stimulation in humans and in animals are only fully compensatory over a limited range of accelerations and velocities. In a previous study (Waespe and Henn, 1979a) we demonstrated that the responses to combined visual-vestibular stimulation are compensatory with accelerations of  $1.25\text{--}10^\circ/\text{s}^2$  and velocities up to  $120^\circ/\text{s}$ . This report describes the responses during combined visual-vestibular stimulation at higher accelerations (up to  $40^\circ/\text{s}^2$ ) and velocities (up to  $160^\circ/\text{s}$ ). It will be shown that even under these more extreme conditions the responses during combined stimulation are compensatory.

## Materials and Methods

Nystagmus was recorded in five Rhesus monkeys (*Macaca mulatta*) chronically prepared with bolts in the skull to fix the head during experiments (Waespe and Henn, 1977a). These monkeys were naive to the experimental situation, with the exception of one, and had not been used before in other experiments. Horizontal and vertical eye position was monitored with chronically implanted DC electrodes. Alertness was maintained by amphetamine ( $0.3\text{--}0.5\text{ mg/kg IM}$ ). Experiments lasted 2 h/day maximum. Animals were seated in a primate chair that was enclosed by a cylinder (124 cm diameter, 86 cm height) covered with alternating vertical black and white stripes, each  $7.5^\circ$  wide. The turntable with the primate chair and cylinder were driven separately by servo-controlled motors.

Stimulation consisted of rotating the monkey in the dark about a vertical axis (pure vestibular stimulation) using a trapezoid velocity profile. The animal was accelerated with  $2.5, 5, 10, 20$ , or  $40^\circ/\text{s}^2$ , turned at constant velocities of  $70\text{--}160^\circ/\text{s}$ , and then decelerated. The cylinder could be rotated around the monkey in the same way (optokinetic stimulation) while it was illuminated from the inside (photopic range). Finally, the monkey was rotated in the light inside the stationary cylinder (combined visual-vestibular stimulation).

Eye movements were calibrated by rotating the optokinetic cylinder at constant velocities of  $15, 30, 45$ , and  $60^\circ/\text{s}$ . At these values, stimulus and eye velocities can be considered to be equal and form a straight line when plotted against each other. Linear regression lines were calculated and the value obtained at  $30^\circ/\text{s}$  taken as reference point with a gain of unity for further calculations. Animals were kept light-adapted except for the short periods of vestibular stimulation (less than 90 s). No effort was taken to compensate for transient variations in the corneo-

retinal potential (Kris, 1958). Slow-phase nystagmus velocity was obtained by differentiating the horizontal eye position signal. In the figures of this report the large signals representing the fast phases of nystagmus were clipped at an arbitrary level. The decremental time constant of the nystagmus slow-phase velocity was taken as the time elapsed between the end of the acceleration and the point at which the velocity was slowed down to a value of  $1/e$  (37%) of the maximum. Data were written out on a rectilinear oscillograph from which further measurements were taken.

## Results

### *A. Nystagmus During Acceleration*

In the analysis of nystagmus, slow-phase velocity was related to the instantaneous stimulus velocity which increased with different rates ( $2.5\text{--}40^\circ/\text{s}^2$ ). The gain of nystagmus was defined as the ratio between nystagmus and stimulus velocity. The gain of the vestibular nystagmus (VN) was found to depend on the value and duration of acceleration. Initially, up to about  $40^\circ/\text{s}$  the gain is above 0.8 for all accelerations applied (Fig. 4D). At velocities exceeding  $40^\circ/\text{s}$ , gain progressively falls for low acceleration values (Fig. 4A, Table 2). The gain of the optokinetic nystagmus (OKN) also depends on the value and duration of the cylinder acceleration. Gain rapidly falls with accelerations above  $5^\circ/\text{s}^2$  and velocities above  $60\text{--}80^\circ/\text{s}$  (Figs. 4B and E, Table 2). There are considerable differences between individual monkeys (Table 1). With  $40^\circ/\text{s}^2$  visual pattern acceleration the monkey in Fig. 2 developed an increasing nystagmus velocity which, during the constant velocity period (after 15–20 s), finally reached and maintained stimulus velocity. The monkey in Fig. 3, however, was unable to develop any appreciable nystagmus during high visual acceleration, although he did so with lower values of visual acceleration.

During combined optokinetic-vestibular stimulation (VN + OKN), i.e., rotation of the monkey in the light inside the stationary cylinder, the gain of nystagmus becomes independent of the value and duration of acceleration (Figs. 1C, 4C, and F). Slow-phase velocity is then only a function of stimulus velocity and gain is always near unity (Tables 1 and 2). This was true for all monkeys independent of individual gains of vestibular or optokinetic nystagmus. In Table 1 also the ranges of averaged gains at the end of the acceleration phase of VN, OKN, and combined responses (VN plus OKN) are shown. The variability of gain is greater for the VN and OKN than for the combined response.

### *B. Nystagmus During Constant Velocity Stimulation*

During rotation with constant velocity, the VN decays with a dominant time constant of 10–31 s (averaged values for each monkey). The time constant varied greatly between monkeys and also individual trials in the same monkey. Two extremes are the monkey in Fig. 2 with a time constant of 8.0 s and the animal in Fig. 3 with a time constant of about 32 s.

Using high acceleration values ( $40^\circ/\text{s}^2$ , up to  $160^\circ/\text{s}$ ) for the visual surround, the OKN reaches a plateau only several seconds after the end of acceleration (Fig. 2B). The maximal value of this plateau, i.e., the saturation velocity of OKN, also differed between monkeys;  $80\text{--}155^\circ/\text{s}$  with a mean value of  $103^\circ/\text{s}$  at a

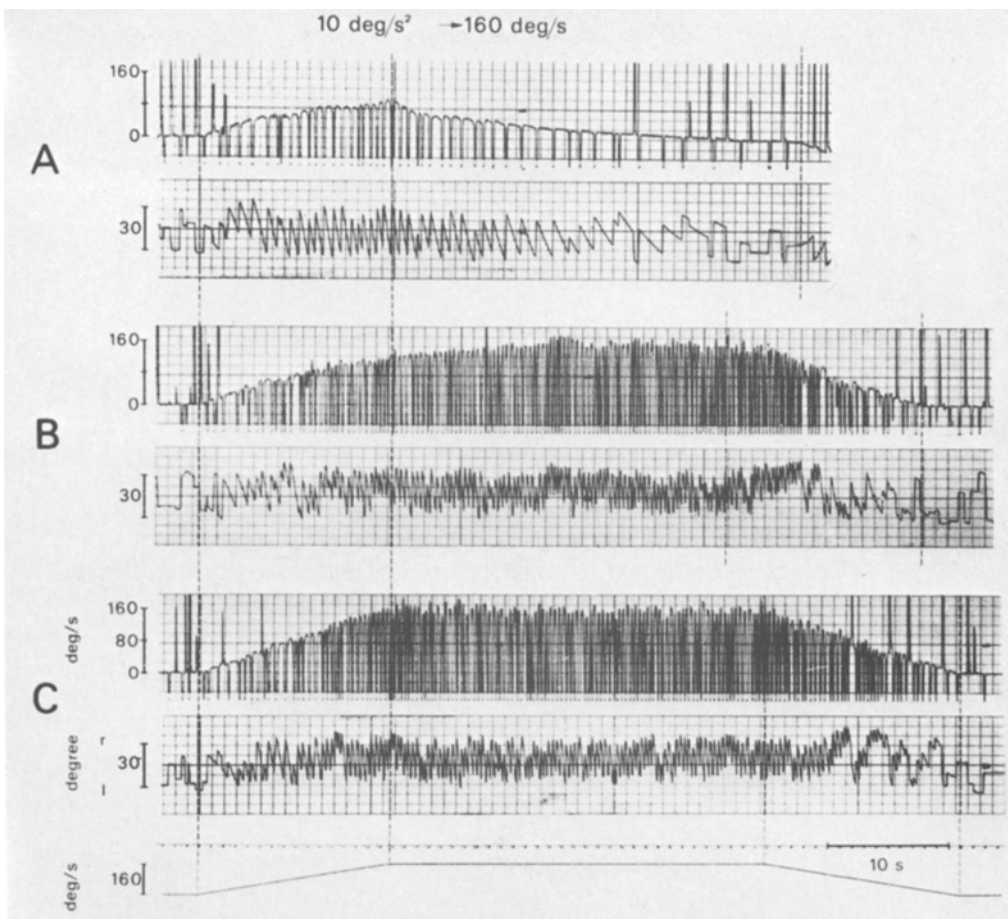
**Table 1.** Gain of nystagmus slow-phase at the end of the acceleration phase of vestibular (VN), optokinetic (OKN), and combined (VN + OKN) stimulation. Averaged values and ranges for four monkeys (see Fig. 4D–F)

Acceleration (degrees/s <sup>2</sup> )	Velocity (degrees/s)	Gain (range)		
		VN	OKN	VN + OKN
5	70	0.71 (0.51–0.86)	0.80 (0.67–0.91)	0.90 (0.84–1.02)
10	100	0.76 (0.71–0.79)	0.65 (0.51–0.76)	0.93 (0.89–1.01)
20	120	0.83 (0.75–0.91)	0.46 (0.38–0.66)	0.91 (0.83–1.02)
40	160	0.89 (0.79–0.94)	0.26 (0.09–0.45)	0.96 (0.94–0.99)

**Table 2.** Gain of nystagmus velocity during vestibular (VN), optokinetic (OKN), and combined (VN + OKN) acceleration. Acceleration (2.5, 10, 40°/s<sup>2</sup>) continued up to a constant velocity rotation of 160°/s. Four different velocity values (40, 80, 120, 160°/s) were selected from the data during the acceleration period (averaged values from two monkeys) (see also Fig. 4A–C for one monkey)

Acceleration (degrees/s <sup>2</sup> )	Velocity (degrees/s)	Gain		
		VN	OKN	VN + OKN
2.5	40	0.85	0.88	0.92
10		0.85	0.75	0.88
40		0.78	0.45	0.75
2.5	80	0.85	0.93	0.96
10		0.89	0.68	0.90
40		0.87	0.45	0.86
2.5	120	0.76	0.86	0.96
10		0.93	0.69	1.0
40		0.93	0.43	0.92
2.5	160	0.61	0.76	0.92
10		0.92	0.68	0.94
40		0.94	0.42	0.92

stimulus velocity of 160°/s. The two monkeys with the lowest saturation velocity had great difficulties in building up nystagmus with an acceleration of 40°/s<sup>2</sup>. In Fig. 3B the maximal slow-phase velocity is only 65°/s and holds only for short periods. The same monkey could easily maintain higher values after lower accelerations, or during constant velocity rotation in the light (Fig. 3C). During combined stimulation nystagmus velocity (VN + OKN) reaches an initial peak immediately at the end of acceleration. It then stays approximately at the same level if end velocity of stimulation is below the optokinetic saturation velocity or declines

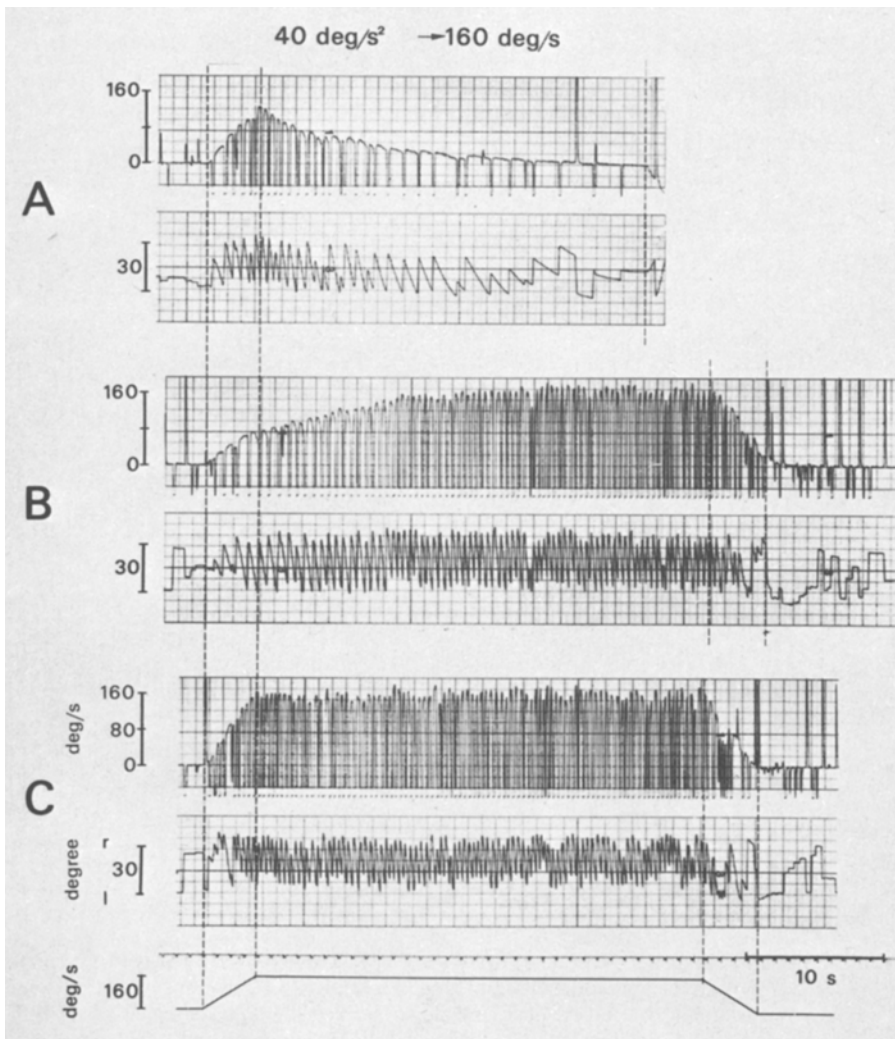


**Fig. 1.** Vestibular nystagmus (VN) in **A**, optokinetic nystagmus (OKN) in **B**, and nystagmus during combined optokinetic-vestibular stimulation (VN + OKN) in **C** in monkey 50: Horizontal eye velocity above, and horizontal eye position below. The monkey (**A**, **C**) or the visual surround (**B**) are accelerated with  $10^\circ/\text{s}^2$  up to  $160^\circ/\text{s}$ ; start and end of acceleration are indicated by dotted lines. After 25–30 s of constant velocity rotation, deceleration ( $10^\circ/\text{s}^2$ ) was started. Note that optokinetic, vestibular, and combined nystagmus velocities are similarly compensatory up to a velocity of about  $50^\circ/\text{s}$

to a level similar to that of optokinetic saturation velocity (mean value  $115^\circ/\text{s}$  at  $160^\circ/\text{s}$  stimulus velocity). Therefore, in most monkeys, the initial high nystagmus velocity fell over several seconds. Only one monkey (Fig. 2C) could continuously maintain a velocity of almost  $160^\circ/\text{s}$ .

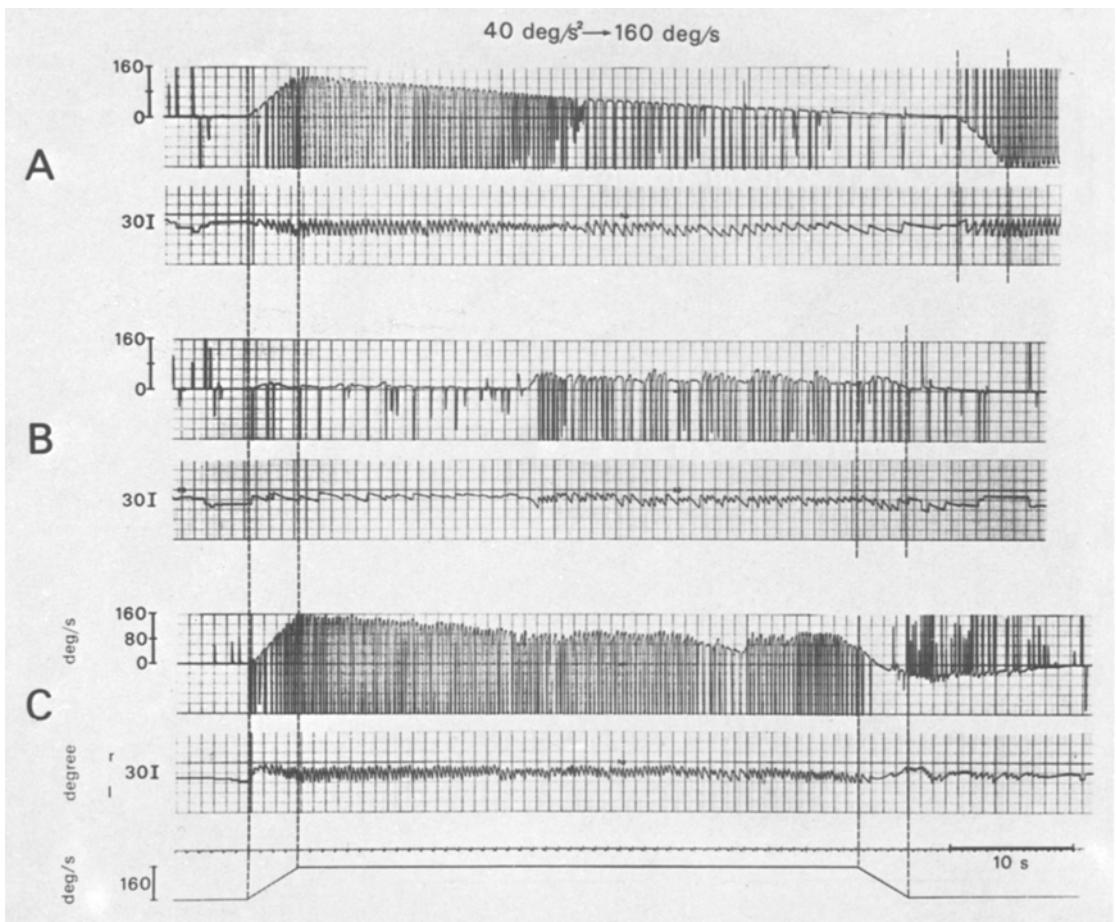
### *C. Nystagmus Slow-Phase Velocity During Deceleration*

During deceleration in complete darkness, nystagmus (VN) was usually symmetrical with the response during acceleration. Sometimes, however, gain was greater



**Fig. 2.** VN, OKN, and combined nystagmus response in the same monkey as in Figure 1. Acceleration and deceleration are  $40^\circ/\text{s}^2$ , constant velocity rotation  $160^\circ/\text{s}$ . Note the short decay time constant of the VN of about 8 s in **A** and the slow rise of nystagmus in **B** during optokinetic stimulation. Only during combined stimulation in **C**, nystagmus velocity faithfully follows stimulus velocity during all phases of stimulation

than unity. This can be expected if secondary perrotatory nystagmus superimposes. During deceleration of the cylinder, nystagmus (OKN) slow-phase velocity closely followed the decreasing stimulus velocity if deceleration was less than  $10^\circ/\text{s}^2$ . With higher deceleration values, nystagmus outlasted the deceleration period and continued in the light over several seconds (Fig. 5B). With the preceding velocity *above* the OKN saturation, nystagmus decline was initially very slow; *below* the saturation velocity it declined more rapidly to a velocity of



**Fig. 3.** VN, OKN, and combined nystagmus response in monkey 57. Format as in previous Figures. Note that the VN in A shows some asymmetry with greater values during the deceleration. The OKN in B takes a long time to develop and reaches only small velocities. It outlasts the end of deceleration as OKAN. In C, combined stimulation, during the constant velocity rotation, nystagmus decays and maintains a velocity of about 95 deg/s, the saturation of OKN for that animal. During deceleration nystagmus reverses with a peak 3 s after the end of deceleration

30–50°/s. Then the decline decreased and eye velocity could be faster than the further decreasing stimulus velocity (Fig. 5B). A deceleration of 40°/s<sup>2</sup> from 160°/s produced a decay of OKN that continued within the stationary visual surround on the average for 5.5 s (range 0–11 s). During deceleration of the monkey in the light, responses (VN + OKN) were different depending on the preceding OKN velocity. Deceleration from a velocity *below* OKN saturation, nystagmus always closely followed the decreasing stimulus velocity independent of the value or duration of deceleration (Fig. 5C). Deceleration from a velocity *above* OKN saturation could result in a reversal of nystagmus already during the deceleration phase (Fig. 3C). In three monkeys, deceleration of 40°/s<sup>2</sup> from a velocity of 160°/s resulted in a peak





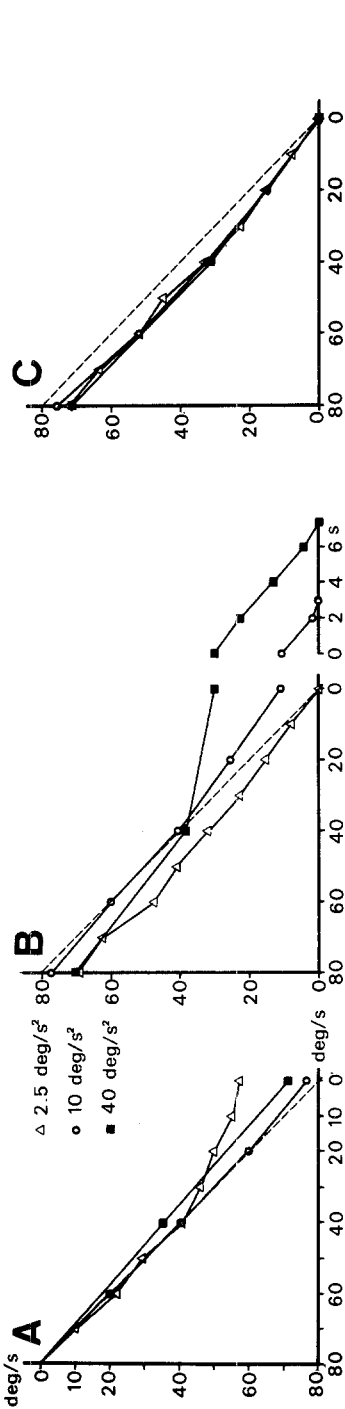


Fig. 5. Nystagmus velocity during deceleration of the monkey in darkness (A), deceleration of the visual surround (B) and deceleration of the monkey in the light (C). The foregoing constant velocity of rotation was 80°/s, i.e., well below the OKN saturation velocity. Averaged values of four trials. Abscissa is the decreasing stimulus velocity. In B after the end of deceleration a time scale is added. Ordinate is nystagmus slow-phase velocity, which increases in A (VN), but decreases in B (OKN) and C (combined response). Note that the OKN outlasts the end of deceleration by several seconds. During combined stimulation nystagmus decays with stimulus velocity independent of rate of deceleration

velocity of reversed nystagmus of  $29.5^\circ/\text{s}$ . The difference between the foregoing stimulus velocity and the nystagmus velocity averaged  $63^\circ/\text{s}$ . Reversed nystagmus decayed with a time constant of 7 s (range 0.5–13 s). In one monkey, reversed nystagmus occurred at a deceleration rate of  $10^\circ/\text{s}^2$ , in two others, only at  $20^\circ/\text{s}^2$ .

## Discussion

The results of the present study on the interaction of the vestibular and optokinetic nystagmus in naive monkeys demonstrate that during combined optokinetic-vestibular acceleration both reflexes combine in such a way that nystagmus velocity is only a function of the instantaneous velocity with a gain near unity. The nonlinearities of the optokinetic or vestibular system compensate for each other so that nystagmus velocity becomes independent of the duration and value of acceleration. Only during constant velocity rotation is the working range limited by the OKN saturation velocity (Cohen et al., 1977). It varies greatly between monkeys. This study confirms and extends similar findings with lower acceleration values ( $1.25\text{--}10^\circ/\text{s}^2$ ) (Waespe and Henn, 1979a). We showed that strong asymmetries in vestibular responses are compensated by the visual input. The response characteristics of the vestibular system are greatly improved by the additional visual input. The achievement of this fully compensatory response during visual-vestibular stimulation is independent of the vestibular performance in the dark, which can vary considerably between monkeys. The limits of this immediate compensation by the visual input has yet to be investigated. The value of the saturation velocity of the OKN plays an important role during deceleration of the monkey in the light. As long as monkeys were decelerated from a velocity below the saturation velocity (or immediately after the end of acceleration) nystagmus velocity is always a function of the instantaneous stimulus velocity independent of the deceleration rate. Deceleration with  $10^\circ/\text{s}^2$  or more from a velocity above the saturation velocity of OKN could lead to nystagmus reversal.

Experiments similar to those reported here, using either trapezoid or sinusoidal stimulation, have been done in rabbits (Baarsma and Collewijn, 1974; Batini et al., 1979) and man (Lau et al., 1978; Koenig et al., 1978). They all agree that during combined stimulation the linear working range of the system is extended. However, they also show that the dynamics of the vestibulo-ocular reflex (VOR) and of the OKN differ in different species. Thus, the gain of the VOR varied between 0.4 in man (Meiry, 1971; Koenig et al., 1978) and up to 0.85 or more in monkeys (Skavenski and Robinson, 1973; Buettner et al., 1978). Furthermore, the gain of the VOR can depend on several extravestibular factors (Barr et al., 1976; Benson et al., 1966). In previous studies we have analyzed the activity of single cells in the vestibular nuclei during visual-vestibular interaction and have tried to relate it to the oculomotor output (Waespe and Henn, 1977a, b, 1978, 1979a, b). One aspect was that vestibular nuclei neurons saturate at lower optokinetic stimulus velocities (average  $60^\circ/\text{s}$ ) than nystagmus slow-phase velocity. During combined visual-vestibular stimulation both inputs combine in such a way that the neuronal signal is also only a function of the instantaneous velocity, independent of the acceleration applied. The linear range of this combination was different for different neurons. The

results suggest that the overall neuronal activity of the vestibular nuclei cannot solely account for the oculomotor response. Other neuronal structures are needed to extend the range of visual-vestibular interaction. Several reports (Ito, 1979; Lisberger and Fuchs, 1978; Miles and Fuller, 1975; Robinson, 1976; Takemori and Cohen, 1974) and present experiments in our laboratory (Waespe and Henn, 1979c) indicate that the flocculus might be involved in such interactions.

*Acknowledgements.* Supported by a grant from the Swiss National Foundation for Scientific Research 3.343.78. We thank Mr. E. Solcà for taking care of the electronic equipment and Mr. J. Müller for photographic work.

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Received March 8, 1980