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Contribution of the maculo-ocular reflex to gaze stability in the rabbit

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Summary. The contribution of the maculo-ocular reflex to gaze stability was studied in 10 pigmented rabbits by rolling the animals at various angles of sagittal inclination of the rotation and/or longitudinal animal axes. At low frequencies (0.005–0.01 Hz) of sinusoidal stimulation the vestibulo-ocular reflex (VOR) was due to macular activation, while at intermediate and high frequencies it was mainly due to ampullar activation. The following results were obtained: 1) maculo-ocular reflex gain decreased as a function of the cosine of the angle between the rotation axis and the earth's horizontal plane. No change in gain was observed when longitudinal animal axis alone was inclined. 2) At 0° of rotation axis and with the animal's longitudinal axis inclination also set at 0°, the maculo-ocular reflex was oriented about 20° forward and upward with respect to the earth's vertical axis. This orientation remained constant with sagittal inclinations of the rotation and/or longitudinal animal axes ranging from approximately 5° upward to 30° downward. When the longitudinal animal axis was inclined beyond these limits, the eye trajectory tended to follow the axis inclination. In the upside down position, the maculo-ocular reflex was anticompensatory, oblique and fixed with respect to orbital coordinates. 3) Ampullo-ocular reflex gain did not change with inclinations of the rotation and/or longitudinal animal axes. The ocular responses were consistently oriented to the stimulus plane. At intermediate frequencies the eye movement trajectory was elliptic because of directional differences between the ampullo- and maculo-ocular reflexes. 4) In the upright position the coactivation of the optokinetic reflex (OKR) eliminated the eye disalignment with respect to the stimulus plane and the elliptic trajectory. 5) Combined vertical OKR and VOR gain in the prone position (VOKR + VVOR 0°) was higher than that of the combined VOKR + VVOR in the 90° nose up position. The VVOR + VOKR 90° gain was in turn higher than the VVOR + VOKR gain in the 180° upside down position. 6) We suggest that, in the dark, the maculo-ocular response tends to reduce the disalignment of both eyes with respect to the horizon rather than inducing oculocompensatory responses. In the light, this maculo-ocular reflex increases the gain of combined optokinetic and vestibular responses.

Key words: Vestibulo-ocular reflex – Optokinetic reflex – Otolithic receptors – Gaze stability – Rabbit

Introduction

It is well known that an important otolithic function is that of stabilizing the visual world on the retina. The contribution of the otoliths to the vestibulo-ocular reflex has been clearly shown in laterally-eyed animals when they are rotated about the interaural or longitudinal axis (Barmack 1981; Van der Steen and Collewijn 1984). Pitching or rolling activates not only the cristae of the vertical canals, but also the otolithic maculae, since the otoliths are sensitive to modulation of the gravity vector component on their functional polarization vector (Flock 1964; Lindeman 1969; Fernandez and Goldberg 1976a; Fernandez and Goldberg 1976b). The vertical vestibulo-ocular reflex (VVOR) is, in fact, a combination of the ampullo-ocular reflex (AOR) and the maculo-ocular reflex (MOR) (Barmack 1981; Van der Steen and Collewijn 1984; Barmack and Pettorossi 1988). The macular contribution to the VVOR produces remarkable gain increase and a phase lead decrease in the vertical AOR within the lower range of stimulation frequencies. In addition to this effect on the slow phase of eye responses, macular activation also suppresses the anticompensatory fast phases (AFPs) usually present in

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Offprint requests to: V.E. Pettorossi (address see above) the horizontal vestibulo-ocular reflex (HVOR) (Barmack 1981). Because of these otolithic influences, vertical ocular stability in the dark is higher than horizontal stability.

An otolithic contribution to gaze stability during centric rotation has also been reported in frontally-eyed animals, though it was very small. For this reason, the otolithic influence on the oculocompensatory responses can be better documented in these animals by stimulating them about an eccentric vertical axis to produce linear acceleration (Gresty and Bronstein 1986; Viirre et al. 1986; Gresty et al. 1987) or about an off-vertical axis, during which the otoliths are stimulated by a rotating component of gravity (Raphan et al. 1981; Harris 1987; Darlot et al. 1988).

However, in spite of our current knowledge about otolithic influences on gaze stability, the oculocompensatory functions of such inputs have not been clearly defined. In fact, the alignment of macular-induced eye responses with the stimulation plane has never been investigated. Moreover, no information is available about the gain or direction of the maculo-ocular reflex with intermediate degrees of inclination of the rotation or longitudinal animal axis. In frontally-eyed animals, ocular orientation in response to eccentric or off-vertical rotations is difficult to analyze because the MOR interacts with other oculomotor subsystems to produce these responses. In laterally-eyed animals the MOR has been investigated by oscillating the animals only about the longitudinal or interaural axis in the horizontal plane.

Another aspect of otolithic function that requires investigation is the interaction of the maculo-ocular reflex with the optokinetic reflex (OKR). In the light, the eye seems to be stabilized by the OKR within the lower range of stimulation frequencies (Erickson and Barmack 1980; Barmack 1981; Van der Steen and Collewijn 1984). The MOR contribution to gaze stability should thus be insignificant under this condition.

The aims of the present study were to define the orientation of MOR responses and their interaction with the ampullo-ocular reflex, and to clarify the role of the MOR in both darkness and light. We therefore studied the VVOR gain, phase and direction in the rabbit under different experimental conditions. The rabbits were first rolled about their longitudinal axis parallel to the earth's horizontal plane (VVOR 0°). Second, the roll stimulations were performed at various angles of sagittal inclination of the head from $-60°$ to $+30°$ and/or of the rotation axis from $-60°$ to $+30°$.The animals were also rolled in the supine position to analyze the ocular responses resulting from the combination of oppositely directed MOR and AOR (Barmack 1981; Barmack 1987). Third, the VVOR was evaluated in the light in order to study the effect of the optokinetic stimulation on gain and orientation of the vestibulo-ocular responses.

The main findings of this work are: 1) a constant "quasi" vertical orientation of MOR responses regardless of the angle of sagittal inclination of head and rotation axis within a physiological range; 2) a macular enhancement of gaze stability in the light.

Methods

Preliminary surgical procedures

Ten pigmented rabbits were anaesthetized with ketamine hydrochloride (Ketalar Parke-Davis, 50 mg/kg) and diazepam (Valium, Roche, 50 mg/kg). The head was held in a stereotaxic apparatus so that the lambda suture was 1.5 mm below the bregma suture (0° stereotaxic). Two head restraining screws were secured with dental cement to smaller screws fixed to the skull. The animals were allowed to recover for at least 3 days after anaesthesia before the experiment began.

Experimental apparatus

The animals were placed on a servo-controlled 3-axial turntable (3M 3000 Mangoni, Italy). The body was firmly encased in a cradle fixed to the turntable, while the head was secured by means of the head-restraining screws to a stereotaxic frame which could be pitched at various degrees in the sagittal plane. At 0° pitch angle (corresponding to 12° nose down with respect to the stereotaxic 0°) the plane of the lateral semicircular canal lay in the earth's horizontal plane (Barmack 1988).

Eye and table position recording

Eye position was monitored by an infrared light projection technique (Barmack 1988). The eye was anaesthetized (Novesina 0.4%, Sandoz) and a small suction cup with a light emitting diode (LED) was attached to the cornea. The LED projected a narrow beam of infrared light onto a photosensitive X–Y position detector (SC 50; United Detector Technology) 5 mm from the tip of the LED, with its surface parallel to the sagittal plane. X and Y signals were sent to a digital oscilloscope (VKS 22-16, VUKO, West Germany), stored on magnetic tape and plotted with an X–Y recorder (7035 B Hewlett Packard), having a mechanical step size of 0.1 mm.

Ocular torsion was also measured by positioning a second LED orthogonally with respect to the major axis of the suction cup to project the light beam onto a smaller X–Y photosensor (SC 25 United Detector Technology) placed with its sensitive surface in the frontal plane to detect possible ocular torsion during vestibular roll stimulation (see below).The ocular displacement measured by the frontal sensor resulted from the combined torsional and vertical eye movements. To achieve torsional recording alone we subtracted the vertical response measured by the sagittal detector from the combined one. This was made possible by simultaneous or sequential use of the sagittal and frontal photosensors. The X and Y axes of the photosensors were constantly aligned with the horizontal and vertical earth axes respectively. After changing the platform or the animal inclination the position of both detectors was carefully readjusted by means of a spirit-level device so that they were earth fixed. The suction cup was reattached to the cornea to orient the incident centroids perpendicular to the detector surfaces. During the oscillations the photodetectors were maintained fixed to the animal's head. The eye movement transducers were calibrated by moving the LED on a model of the rabbit eye through known horizontal, vertical and torsional angular displacements. They were found to be linear to within 5% for eye displacements of ±15° and to have a sensitivity of 0.2 min of arc. Table movement was measured with a servo-potentiometer.

Vestibular stimulation

Vertical vestibulo-ocular reflex (VVOR) was obtained by sinusoidally oscillating the animal in the frontal plane. Both the rotation axis (RA) and the longitudinal animal axis (LA) could be inclined in the sagittal plane at known angles. The upward direction of inclination was defined as positive. The animal was first oscillated in the frontal plane (roll stimulation) at various angles of sagittal inclination of RA or LA axis. Second, the RA and LA axes were inclined together. Third, the animal was oscillated in a supine position at various angles of inclination of the LA and RA (VVOR 180°, 170°, 190°). Fourth, the torsional vestibulo-ocular reflex (TVOR) was tested by sinusoidally oscillating the animal in the sagittal plane (pitch) at 0.005 Hz. In all the trials, the stimulus parameters were chosen as follows: sinusoidal amplitude equal to 20° peak-to-peak (20° p-p); stimulation frequencies from 0.005 to 0.8 Hz.

Combined vestibular and optokinetic stimulation

The above reported vestibular stimulations were repeated after placing a lighted screen consisting of a black and white random dot pattern (elements 2 degrees wide) in front of the eye controlateral to the recording one, filling about 80% of the monocular visual field. The stimulus parameters were the same as those used for the vestibular stimulation alone.

Optokinetic stimulation

Optokinetic stimulation was performed by securing the screen described above to the turntable at the correct distance from the animal, which in turn was fixed in space by suspending its cradle to an external reference apparatus. The screen was sinusoidally oscillated at frequencies from 0.005 Hz to 0.6 Hz at amplitudes of 10°, 20°, 30° peak-to-peak with the animal placed in the prone position (vertical optokinetic reflex: VOKR 0°). Testing was also done in the nose up position (VOKR 90°) and in the supine position (VOKR 180°) in the same range of frequencies reported above at 20° peak-to-peak of stimulus amplitude. Differences between the stimulated and the recorded eye movements are not reported (Barmack and Erickson 1980).

Data analysis

The gain of the ocular responses was obtained by comparing the amplitude of the ocular responses with the amplitude of the table movement. The phase (eye position + 180° compared to table position) was measured at each half-cycle of rotation. The direction of the ocular responses was studied by plotting the horizontal and the vertical eye displacements in X and Y axes respectively. Gains and phases were compared using Student's test.

Results

Vertical vestibulo-ocular reflex (VVOR) at different inclinations of both rotation (RA) and longitudinal animal axes (LA)

VVOR 0° was tested by rolling the animal about its longitudinal axis lying in the earth's horizontal plane. This stimulation evoked compensatory eye responses without anticompensatory fast phases. Gain and phase values were similar to those previously reported (Barmack 1981; Van der Steen and Collewijn 1984) (Fig. 1). The higher gain observed in the low range of stimulation frequencies and the reduction of the phase advance compared to horizontal vestibulo-ocular reflex (HVOR), as well as the absence of anticompensatory fast phases (AFPs) have been attributed to maculo-ocular reflex (MOR) which combines in the vertical plane with the ampullo-ocular reflex (AOR) (Barmack 1981; Barmack and Pettorossi 1988).

The ocular responses of macular origin (0.005 Hz of stimulation frequency) were misaligned compared to the stimulation plane with the eye moving forward and upward (20° inclination with respect to the earth's vertical frontal plane) (Fig. 2). Conversely, the ocular responses with a 0.8 Hz stimulation frequency, due to ampullo-ocular reflex, were coplanar with the stimulation plane. In the intermediate range of stimulation frequencies, in which the maculo-ocular reflex combines with the ampullo-ocular reflex, the trajectory of the ocular responses was elliptic (Fig. 3). The addition of the vertical optokinetic reflex (VOKR) to VVOR 0° caused the gain to reach values of up to 0.9 (Fig. 1) and eliminated any misalignment with the stimulation plane (Fig. 2).

When the animal was rolled about its longitudinal axis inclined 90° with respect to the earth's horizontal

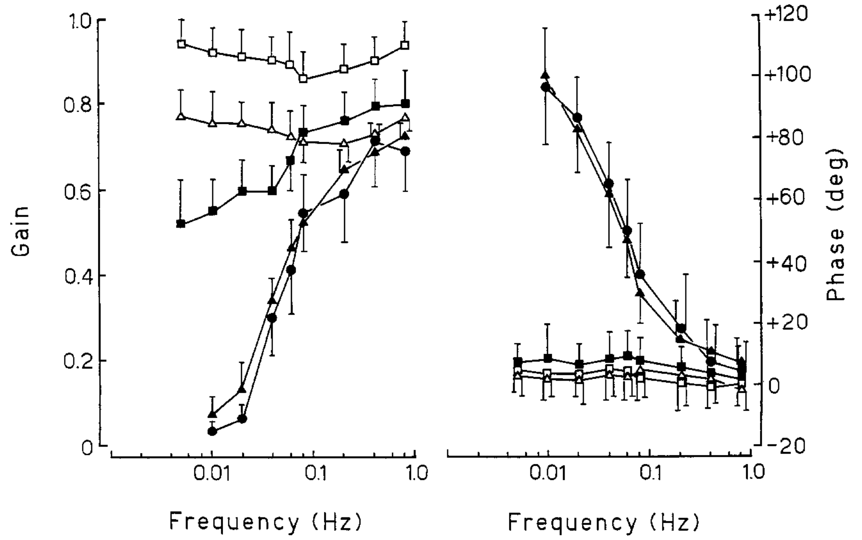

Fig. 1. Comparison of the phase and gain of horizontal vestibulo-ocular reflex (HVOR) (filled circles), vertical vestibulo-ocular reflex (VVOR) 0° (filled squares), VVOR 90° (filled triangles), vertical optokinetic reflex (VOKR) + VVOR 0° (open squares) and VOKR + VVOR 90° (open triangles). The mean gain and phase (referred to 180°) as a function of frequency are illustrated for 10 rabbits. Bars indicate one standard deviation for each data point

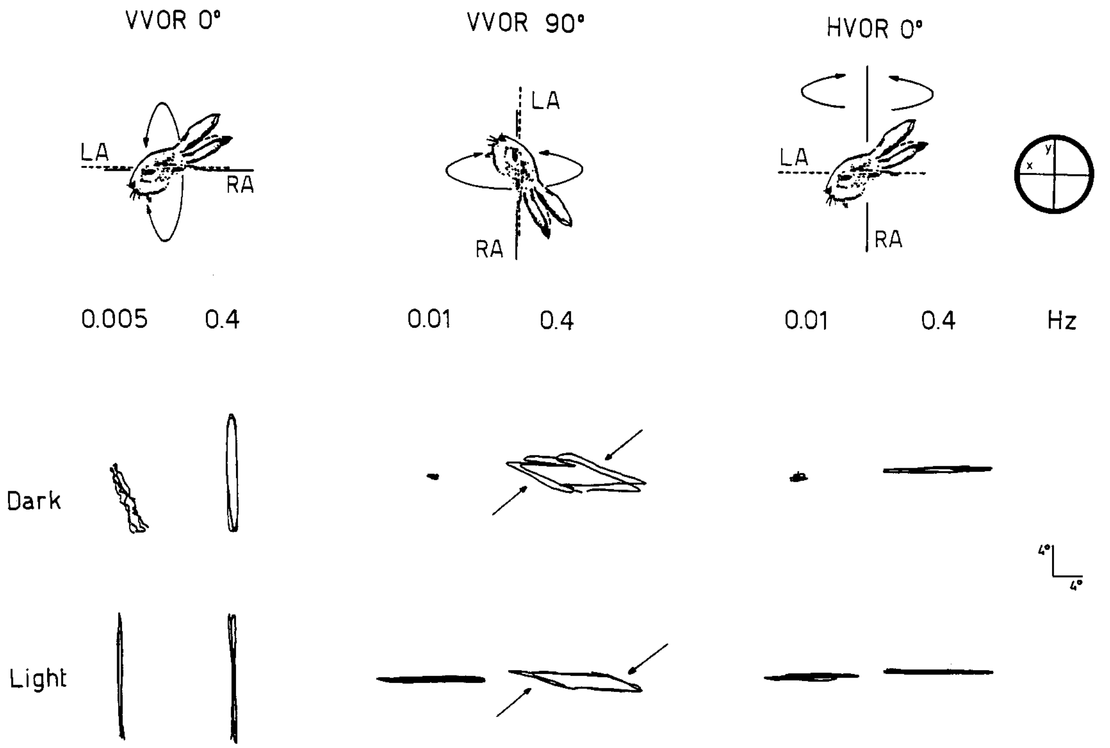

Fig. 2. Eye responses to vestibular and optokinetic stimulations at different orientations for the rotation (RA) and longitudinal animal (LA) axes. Left column: VVOR 0°; middle column: VVOR 90°; right column: HVOR 0°. The schematic at the top shows the animal's position and the plane of the stimulus. The photosensitive X–Y position detector (right side) is maintained fixed in space with the X axis parallel to the horizon. At the bottom, the eye response in the dark (upper row) and in the light (lower row) are shown. Note in VVOR 0° dark, at 0.005 Hz, the ocular trajectory was misaligned with respect to the stimulus. At all the other frequencies compensatory slow phases (CSPs) were coplanar to the stimulation plane. Anticompensatory fast phases (AFPs) which occurred in VVOR 90° and in HVOR 0° (light and dark) were indistinguishable from the CSPs found with horizontal stimulation while they were clearly visible in VVOR 90° (arrows) because they were oblique

plane (VVOR 90°), the ocular responses were due only to AOR because of the lack of macular modulation (Barmack 1981; Barmack and Pettorossi 1988). A decrease in gain and an increase in phase lead with respect to VVOR 0° were observed in the low range of the tested frequencies (Figs. 1, 2). Anticompensatory fast phases appeared as in the HVOR, but they were less frequent and oblique in trajectory. By adding VOKR to VVOR 90°, the gain increased to 0.8 and the phase was close to 0° throughout the tested frequencies. This gain was significantly lower than that observed in VOKR + VVOR 0° by about 0.15 ($p < 0.001$) (Fig. 1). AFPs were also present in the light.

The animals were also stimulated with various angles of sagittal inclination for both the rotation (RA) and longitudinal animal axes (LA) (+30° to −60°) (Fig. 3). By inclining RA + LA downward or upward the gain of the maculo-ocular responses (0.005 Hz) decreased because of the reduction of the macular contribution to VVOR. It appeared that the gain value decreased as a function of the cosine of the angle between the rotation axis and the earth's horizontal plane (Barmack 1981; Fernandez and Goldberg 1976b) (Fig. 4). Ocular responses remained inclined 20° forward and upward with respect to the earth's vertical in a range of sagittal inclination from −30° to +5°. Outside this range, MOR

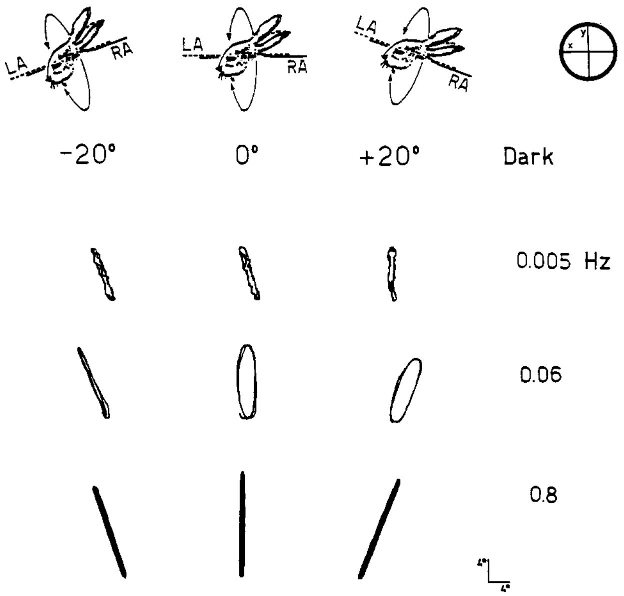

Fig. 3. Ocular responses to sinusoidal roll stimulations with a sagittal inclination of the rotation axis (RA) and longitudinal animal axis (LA) of −20°, 0° and +20°. Eye trajectories at 0.005 Hz were misaligned with respect to the stimulus at 0° and +20° of sagittal inclination, while at 0.8 Hz they were always coplanar. In the intermediate range of stimulation frequencies the eye movements were elliptic

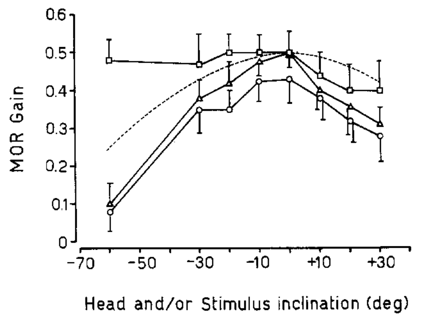

Fig. 4. Maculo-ocular reflex (MOR) gain (0.005 Hz of stimulation frequency) as a function of the angle of sagittal inclination for the rotation axis (RA) (triangles), longitudinal animal axis (LA) (squares) and RA + LA (circles). The MOR gain progressively decreased by changing the sagittal inclination in the upward and downward direction except when LA was inclined. The dashed line indicates the predicted maximum gain value as a function of the cosine of the angle between RA and earth's horizontal plane

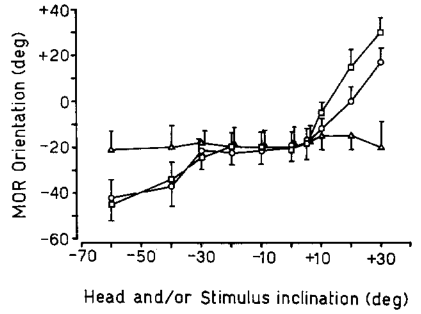

Fig. 5. Maculo-ocular reflex (MOR) orientation (0.005 Hz of stimulation frequency) as a function of the angle of sagittal inclination for the rotation axis (RA) (triangles), longitudinal animal axis (LA) (squares) and RA + LA (circles). In the physiological range (+5° to −30°) the ocular responses remained 20° misaligned from the vertical when LA, RA or LA + RA were inclined. Beyond these limits, MOR responses changed their direction by different amounts in both the upward and downward direction. By modifying only RA inclination, no change in MOR orientation was observed

changed orientation depending upon the direction of sagittal inclination (Figs. 3, 5).

The ampullo-ocular reflex always remained in the plane of the stimulus (Fig. 3). In the range in which MOR and AOR combined, the trajectory of eye movements described an ellipse (Fig. 3). The minor diameter of the ellipse was directly related to the angle between the MOR and AOR planes (MOR–AOR discrepancy, Fig. 3) and inversely related to the frequency of stimulation until it became null at the highest frequencies (Fig. 6).

The addition of VOKR to VVOR besides increasing the gain (Fig. 1) also eliminated differences between the plane of the stimulation and ocular responses (Fig. 6).

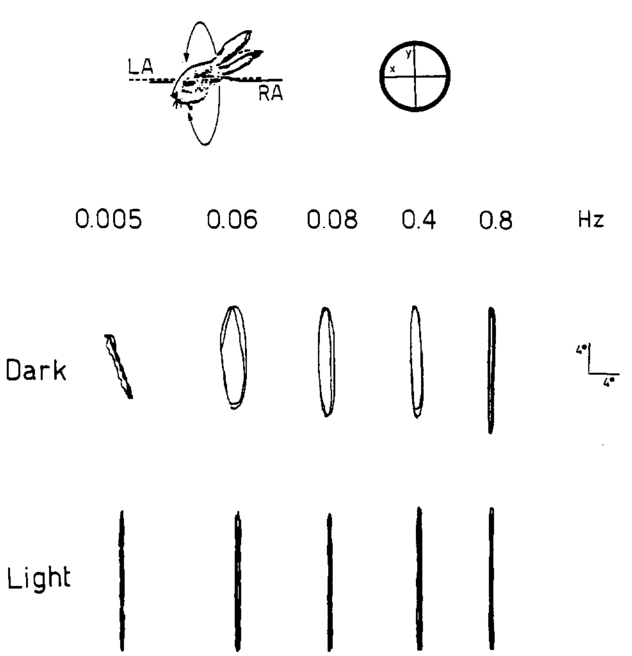

Fig. 6. Eye response trajectories of VVOR 0° at different frequencies of stimulation (0.005 Hz–0.8 Hz) in the dark and in the light. The rotation axis (RA) and longitudinal animal axis (LA) were oriented at 0°. In the range of frequencies for which the maculo-ocular reflex (MOR) and ampullo-ocular reflex (AOR) combined, eye trajectory was elliptic. In the light, the ocular responses showed higher gain and were always coplanar with the stimulus

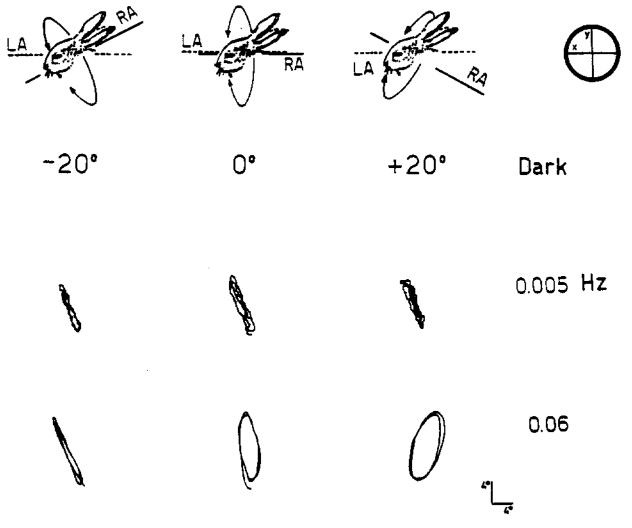

Fig. 7. VVOR at various rotation axis (RA) sagittal inclinations. The trajectory of maculo-ocular reflex (MOR) (0.005 Hz) remained almost constant in a "quasi" vertical plane at various stimulus inclinations. At intermediate frequencies (0.06 Hz) of stimulation, eye movements described an elliptic trajectory due to MOR and ampullo-ocular reflex (AOR) directional discrepancy

VVOR at different rotation axis (RA) inclinations

RA was inclined at various angles in the sagittal plane (from −60° to +30°) while the longitudinal animal axis remained at 0°. As in the previous condition, the gain of maculo-ocular responses (0.005 Hz) decreased in the same way as the cosine of the angle between RA and the earth's horizontal axis (Fig. 4). Furthermore, MOR remained oriented 20° forward and upward at every rotation axis inclination (Figs. 5 and 7).

By adding VOKR to VVOR, the gain of the ocular responses was enhanced and directional discrepancies were eliminated.

VVOR at different longitudinal animal axis (LA) inclinations

By inclining the LA without changing RA, the magnitude projection of the gravity vector on the macular plane was constant while the angle between the gravity vector and the macular plane was modified. From +30° to −60° of longitudinal animal axis inclination MOR gain remained almost constant showing only a small decrease in the upward direction (Fig. 4).

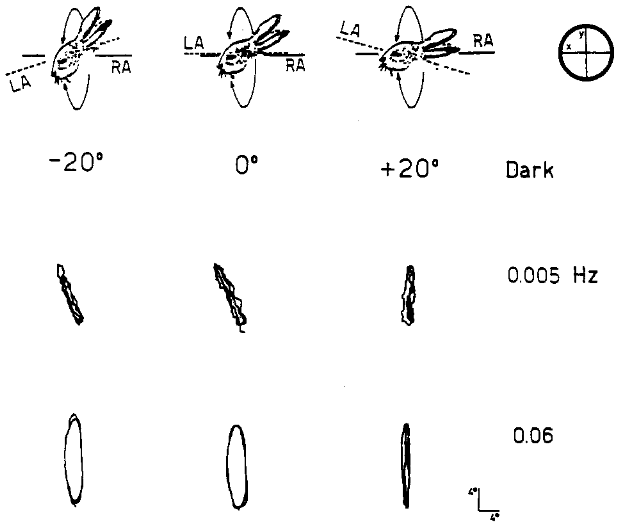

Fig. 8. VVOR at various longitudinal animal axis (LA) sagittal inclinations. Maculo-ocular reflex (MOR) maintains the same orientation at 0° and −20° of LA inclination. At +20° the ocular responses tended to follow the inclination plane. In the intermediate range of frequencies (0.06 Hz) an elliptic trajectory was evident when misalignment existed between ampullo-ocular reflex (AOR) and MOR orientation

The orientation of maculo-ocular responses remained fixed in a plane inclined at about 20° forward and upward with respect to the earth's vertical axis (Figs. 5 and 8) within a range from −30° to +5° of sagittal inclination. Outside this range the ocular responses tended to follow LA inclination in the upward direction more than in the downward one. The ampullo-ocular reflex (0.8 Hz) always remained vertical, i.e. in the plane of the stimulus.

When VOKR stimulation was added to the vestibular one, ocular responses showed both a constant gain close to 0.9 and phase close to 0°. Directional discrepancies also disappeared at low as well as at high stimulation frequencies.

Torsional vestibulo-ocular reflex (TVOR)

The TVOR was tested by oscillating the animal in the sagittal plane at 0.005 Hz in the dark and in the light, obtaining gains of 0.3 and 0.5 respectively. Torsional eye movements were checked also during roll stimulation at different head positions: no significant eye torsion was recorded when the animal was oscillated within a range of +30° to −60° of RA and LA axis sagittal inclinations.

VOKR at different head inclinations

The vertical optokinetic reflex was tested at various amplitudes and frequencies of stimulations (left side, Fig. 9). By changing the amplitude from 10° to 30° a reduction in gain from 0.95 to 0.6 at 0.005 Hz was observed. Similarly, an increase in stimulus frequency reduced the gain. In contrast, by changing the animal's position, there was no difference in VOKR gain (Fig. 9, right side).

VVOR in the supine rabbit (VVOR 180°)

The VVOR 180° was evoked by rolling the animal in the supine position with the LA in the horizontal plane. The

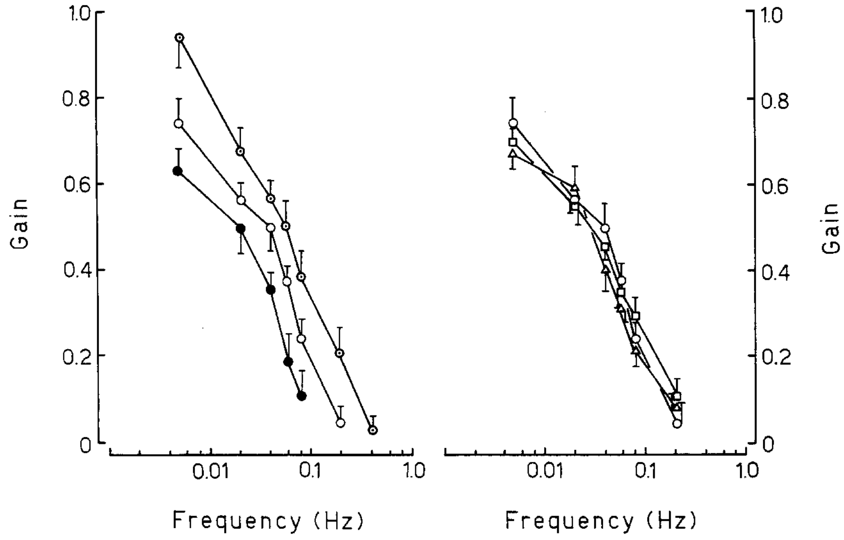

Fig. 9. Vertical optokinetic reflex (VOKR) mean gain as a function of frequency is illustrated for 10 rabbits. On the left the amplitudes of sinusoidal stimulation were 10° (dotted circles), 20° (empty circles) and 30°(filled circles). On the right, a VOKR obtained at 20° of amplitude is shown when longitudinal animal axis (LA) was at 0° (circles), 90° (triangles) and 180° (squares). Bars indicate one standard deviation for each data point

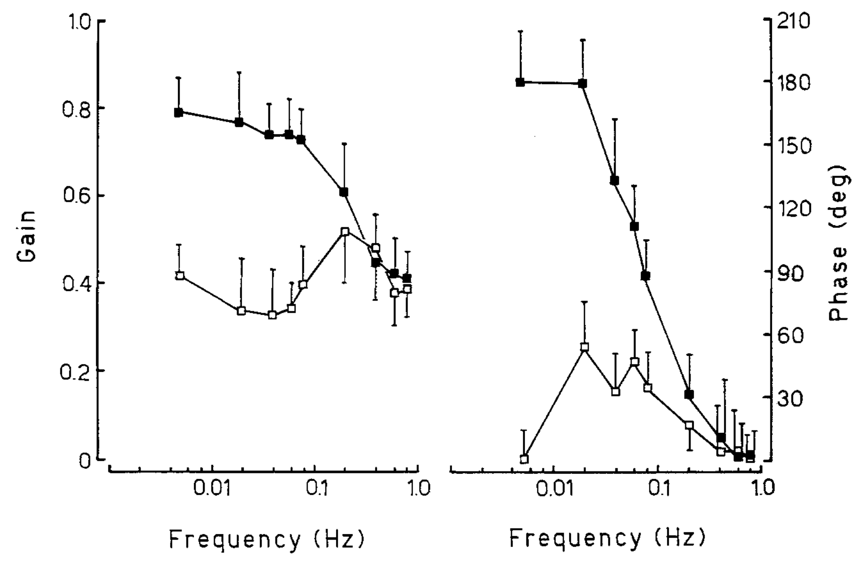

Fig. 10. Comparison of the gain and phase of VVOR in supine rabbits in the dark (filled symbols) and in the light (open symbols). The mean gain and phase (re 180°) as a function of frequency is shown for 10 rabbits. Bars indicate one standard deviation for each data point

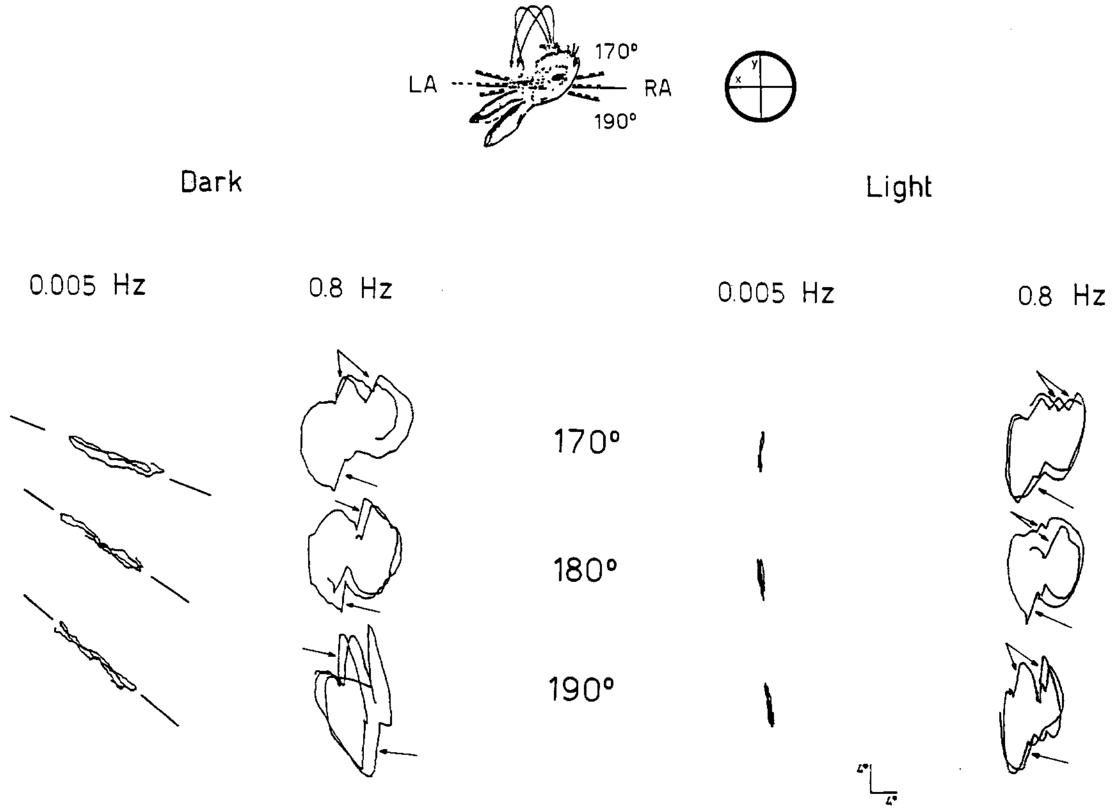

Fig. 11. VVOR in supine rabbit at different rotation axis (RA)+longitudinal animal axis (LA) inclinations (170°–180°–190°). Maculo-ocular reflex (MOR) (0.005 Hz) was about 45° inclined with respect to the stimulation plane at different RA+LA inclinations. At higher frequencies (0.8 Hz), the ocular responses showed circular trajectories interrupted by anticompensatory fast phases (AFPs) (arrows). In the light at 0.005 Hz (MOR+OKR) the responses were coplanar with respect to the stimulus and show a lower gain than pure MOR. At 0.8 Hz elliptic trajectories and AFPs (arrows) were still present

gain was higher than that of VVOR 0° in the range between 0.005 and 0.1 Hz, and it was lower between 0.2 and 0.8 Hz. The ocular responses were anticompensatory at 0.005 Hz while they were compensatory at 0.8 Hz (Fig. 10). The gain and phase characteristic of VVOR 180° could be explained by taking into consideration that: 1) the macular responses in the supine position were anticompensatory while the ampullar responses were compensatory; 2) MOR 180° gain was about twice the MOR 0° gain (MOR 180° gain = 0.8; MOR 0° gain = 0.5). The orientation of the ocular responses at 0.005 Hz was oblique making an angle of 45° with the stimulation plane. Unlike VVOR in the prone position, MOR changed its spatial orientation, maintaining a fixed orbital reference when the rotation and longitudinal animal axes were inclined by ±10°. In the intermediate range of tested frequencies (0.02–0.2 Hz), ocular responses showed a circular trajectory interrupted by oblique anticompensatory fast phases (AFPs). At the highest frequencies, the eye movements described an elliptic trajectory (Fig. 11). The addition of the VOKR changed the gain, phase and orientation of the ocular responses (Fig. 10). At low and intermediate frequencies of stimulation (0.005–0.1 Hz) VOKR reduced the gain to about 0.4, abolished horizontal displacements and reduced the phase lead. At high frequencies the phase tended to reach 0°, the gain had a value of about 0.5, but the trajectory of the slow phases was still elliptic and was interrupted by oblique AFPs.

Discussion

It has been well documented that the maculo-ocular reflex (MOR) contributes to eye stability by enhancing the vertical vestibulo-ocular reflex (VVOR) gain and decreasing the phase in the lower range of stimulation frequencies (Barmack 1981; Van der Steen and Collewijn 1984).

However, the present study showed that the maculo-ocular reflexes are misaligned with respect to the stimulation plane. In fact, when the roll stimulation axis was exactly horizontal, maculo-ocular responses were not vertical but rather inclined 20° forward and upward. When the stimulation axis was inclined, this quasi-vertical orientation was maintained, producing further increases in the misalignment between stimulus and ocular responses. This result was expected because the angle between gravity and the functional polarization vectors of the receptors remained constant. In this case, the effect of the ocular response misalignment was only partially attenuated by the MOR gain decrease due to the reduction in gravity modulation on the maculae. Although the MOR did not follow the stimulation plane, the responses had a clear orientation within the space coordinate system. When the animal's longitudinal axis was inclined within the physiological range, ocular responses remained fixed in space and the MOR gain remained high.

Maintenance of spatial, as opposed to orbital, reference requires a readjustment of the extraocular muscle (EOM) activation pattern whenever the head changes its inclination.

Since the torsional reflex can account for only 33% of the readjustment that occurs in the dark (TVOR gain 0.3) and torsion was not observed during vertical displacements, the reorientation of the EOM activation pattern may have been due to otolithic information. This information might arise from distinct areas of the maculae that are differently activated by the stimulation or from a tonic otolithic signal of the head position relative to gravity. The influence of tonic otolithic input in reflex orientation has been observed at the horizontal cervico-ocular reflex level (Pettorossi et al. 1987).

Thus, it can be concluded that the aim of macular induced eye responses in the dark is to maintain a fixed vertical orientation. By means of the MOR, the eye can minimize the disalignments of the interocular axis with respect to the horizon when the head is displaced in the frontal plane. Furthermore, it is possible that the characteristics of the rabbit's visual fields might, in some way, justify the 20° forward and upward inclination of the MOR responses. Previous studies (Hughes 1971; Collewijn 1981) have shown a fronto-superior overlap of the visual fields of the two eyes with a potential binocular zone of about 24° and a blind zone under and behind the head. The existence of these posterior limits could induce frontally oriented eye responses in an attempt to maintain the largest visual field.

The animals maintained this "quasi" vertical ocular orientation within a limited range of inclination. The nose-down component of this range was much more extensive than the nose-up component. Beyond these limits, eye movement tended to follow orbital coordinates rather than maintaining a fixed spatial reference. When the animal was in the upside down position, the MOR showed a 45° misalignment with respect to the vertical plane; all spatial references were lost and eye movements remained within an orbit-related plane, regardless of the head position. Therefore, the maculae seem to produce correct oculo-postural orientation only within a physiological range of inclination; outside of this range they gradually become less efficient and finally cease to function altogether.

When the maculo-ocular reflex (MOR) and ampullo-ocular reflex (AOR) were combined, eye movement orientation was influenced by the directions of both reflexes: the MOR, which maintained a "quasi" vertical orientation and the AOR, which remained co-planar with the stimulation plane. In fact, within the intermediate range of tested frequencies (0.02–0.2 Hz), in which the two reflexes combine, the eye responses followed an elliptic trajectory. We believe that the maximum diameter of this ellipse is a function of AOR gain, while the minimum diameter is related to MOR gain. In fact the latter diameter decreases with increasing frequency, as does the MOR, and increases as the misalignment between AOR and MOR increases. At high frequencies, where the reflex consists of a pure AOR, the minimum diameter was reduced to almost zero and the trajectory became straight. The 90° phase difference between AOR and MOR (Barmack 1981) is consistent with the elliptic trajectory that we have observed.

In supine animals, MOR not only showed a very high gain, but also considerable misalignment with respect to the stimulation plane. This caused a large directional discrepancy between the MOR and AOR, which resulted in circular eye trajectories within the intermediate frequency range.

In prone animals, the combined vestibular and optokinetic stimulation induced appropriate oculocompensatory responses that were characterized by high gain and a phase of 0° and which were independent of head or plane inclination. The addition of visual input to the VVOR, prevented eye displacements outside the stimulation plane. The contribution of the MOR in these cases appeared small (gain of 0.1–0.2), but significant. In fact, the gain of VVOR 0° in the light was higher than the gain of VVOR 90°. Van der Steen and Collewjin (1984) reported similar differences between the horizontal vestibulo-ocular reflex (HVOR) and the VVOR tested in the light, but they could not determine the cause of these differences. By testing combined vertical optokinetic reflex and vertical vestibulo-ocular reflex (VOKR + VVOR) with the animal in the 90° nose up position, we were able to analyze these reflexes without MOR contribution. By comparing these findings to those obtained at 0°, we can attribute the higher gain of VVOR 0° in the light to the MOR. Furthermore, when MOR was anticompensatory, as it was when the animal was placed in the upside down position, the gain of the combined responses was significantly lower than that observed in VVOR 90° or in HVOR in the light. Since the VOKR gain is not dependent on the animal's position per se (Barmack 1987), these differences in gain might be explained by the fact that, in the upright position, the MOR reduces the retinal slip velocity, while in the upside down position it increases it. These effects on the retinal slip velocity result in optokinetic reflex (OKR) gain changes. In fact OKR gain decreases as retinal slip velocity increases as shown in Fig. 9. The combined MOR + OKR gain can be predicted by adding the OKR gain, estimated on the basis of the effective retinal slip velocity, to the MOR gain. Therefore this results suggest a linear adding between macular and optokinetic responses.

In conclusion, the study that we performed in rabbits allowed us to demonstrate, in a relatively simple way, that the maculo-ocular response tends to reduce the disalignment of both eyes with respect to the horizon rather than inducing oculocompensatory responses. In the light, this maculo-ocular reflex increases the gain of combined optokinetic and vestibular responses.

We do not have any data at this time to confirm that the MOR behaves in this way in other animals, particularly frontally-eyed ones. However we have no reason to believe that our findings will not hold true for these species as well. Investigation in cats are now being undertaken in our lab to verify in these animals the orientation of the maculo-ocular reflex.

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