Torsional optokinetic nystagmus (tOKN) is an ocul motor response occurring when looking at a rotating stimulus. Similar to the horizontal and vertical OKN response, it consists of a slow phase in the direction of the stimulus followed by a fast phase in the opposite direction. Brecher first described the response when he observed the conjunctival blood vessels of a subject that viewed a rotating sectored disc through a telescope.

There are only a few reports in which the tOKN gain (eye velocity in relation to stimulus velocity) to various stimuli has been investigated. Torsional OKN is reported to have a low gain, with values sometimes less than 0.1," compared to horizontal and vertical OKN, where gains can approach 1. There has been no directional preponderance demonstrated for tOKN, with no difference in the response with subjects viewing a target rotating in the clockwise or anticlockwise directions. In all previous reports, there was a small range of stimulus velocities used, the largest range being from 10–80˚/s. Reported gain values were also variable across subjects.

The effects of central and peripheral stimulation on the tOKN response have been investigated in only one previous study, on four subjects. Using a series of artificial central and peripheral masks to occlude various proportions of the stimulus, the authors reported that the tOKN response was dominated by central stimulation.

The absence of central vision in patients with central scotomas due to, for example, age related macular degeneration, has been shown not to significantly affect the horizontal OKN response. It has also been demonstrated that a "filling-in" response occurs in these patients which allows the stimulus to elicit optokinetic nystagmus. In contrast, in normal subjects, the horizontal OKN response is dramatically reduced by occlusion of the central retina. It is of interest to observe, therefore, whether a similar response can occur when using artificial central scotomas to elicit tOKN, since no such response has been commented on previously.

In the current study, we have used video-oculography to systematically investigate the relation between stimulus velocity and tOKN gain using a large range of stimulus velocities, with the aim of establishing the limit and optimum level of response. Secondly, we have examined the effects of central and peripheral stimulation on the tOKN response by varying the size of central and peripheral field.

SUBJECTS AND METHODS

Subjects

A total of 20 healthy subjects, aged 20–59 years, were examined (mean age 34.9 years, 15 women and five men). Eight subjects participated in each experiment. All subjects had normal corrected visual acuity of 6/6 or better in each eye, good stereopsis on the TNO stereotest (between 60 and 15 seconds of arc), and were free from any ophthalmological, otological, or neurological symptoms. All tests were performed without any refractive correction. Six subjects had mild myopia or myopic astigmatism but were able to see the stimuli clearly from a distance of 120 cm without correction. The study received local ethical approval and was performed with consent after explanation of the nature and possible consequences of the study. The study was performed in accordance with tenets of the Declaration of Helsinki.

Methods

Eye movements were measured three dimensionally using a video-oculography technique (VOG), at a sampling rate of 50 Hz (Strabs system, Sensomotoric Instruments GmbH, Teltow, Germany). This consisted of infrared video cameras fitted on to a face mask firmly attached to the head using a rubber strap. Pupil tracking is used to derive horizontal and vertical movements. A segment of the iris is tracked to give torsional eye movements. The system has a spatial resolution of 0.03˚, 0.02˚, and 0.1˚ and a linearity of plus or minus 3.8% full scale reading (FSR), plus or minus 3.2% FSR, and plus or minus 1.4% FSR for horizontal, vertical, and torsional eye movements.
Figure 1  (A) Original recordings of the right eye from one representative subject showing the effect of stimulus velocity on torsional optokinetic nystagmus (tOKN). The stimulus is rotating in the clockwise direction. (B) Median torsional optokinetic nystagmus gain (plus or minus quartiles) of all subjects in response to stimuli rotating at: (i) 3–20°/s at a cycle size of 30°, (ii) 20–120°/s at a cycle size of 30°, and (iii) 20–1000°/s at a cycle size of 90°, in the clockwise and anticlockwise directions.
movements, respectively (company specifications). The range of linear measurement is plus or minus 25°, plus or minus 20°, and plus or minus 18° for horizontal, vertical, and torsional eye movements, respectively. The noise for the current experimental setup was estimated from the torsional recordings as 0.1–0.2° root mean squared (RMS) for torsional angle and 0.1–0.15° RMS for torsional velocity.

Each sample is an integration over a 20 ms period. The three dimensional VOG technique samples at a lower rate compared to the scleral search coil method (50 Hz compared to >250 Hz) and is not suitable for investigating fast phase parameters of nystagmus such as main sequence. However, the non-invasive nature of the VOG technique provides the advantage of allowing longer and more comfortable test periods to the subject.

The digitised ASCII file output for horizontal, vertical, and torsional data was converted into Spike 2 software files (Cambridge Electronic Design, UK) for subsequent analysis. Every subject sat upright with their head stabilised on a chin rest placed 120 cm away from the stimulus. There were no head movements observed during testing in all subjects. The height of each subject was adjusted so that the subject’s eyes and the centre of the stimulus were at the same level. The cameras of the VOG system were adjusted with the lights extinguished and the subject viewing a stationary stimulus.

The subject was asked to fixate the centre of the stimulus. The initial image measured when setting up the recording. The larger cycle size was used for faster angular velocities to limit counter-rotational stimulus projection effects and ensure good stimulus visibility by all subjects.

The subject was asked to fixate the centre of the stimulus binocularly and not to focus on any particular point of the stimulus. Each stimulus was presented for a period of 30 seconds followed by a blank phase of 15 seconds consisting of a black screen during which the subject was asked to continue to centrally fixate the stimulus.

Experiment 2 was designed to investigate the effect of central and peripheral stimulation on the gain of tOKN. To measure the effects of central stimulation, a sinusoidal grating pattern of cycle size 90° was projected at 2.86°, 6.2°, 1024 pixels). The stimuli were generated using a visual stimulus generator (VSG 2/5, Cambridge Research Systems, Rochester, UK). The stimuli consisted of a rotating sinusoidal grating pattern of either a 30° or 90° cycle size subtending a maximum of 50.8 degrees in diameter (for example, see insets in fig 1B). The luminance of the grating pattern varied from 0.45 candelas/m² to 23 candelas/m² giving a luminance contrast of 96%. The stimulus was revolved around its central axis in both clockwise and anticlockwise directions to generate tOKN with variations in its velocity, cycle size and area of stimulation for different experimental conditions. All references to stimulus direction below are given from the perspective of the subject.

Experiment 1 was devised to measure the effect of stimulus velocity on the gain of tOKN. Stimulus velocities ranging from 3˚/s to 1000˚/s were used, the whole range of stimulus velocities was tested in three stages:

Stage 1: A sinusoidal grating pattern of cycle size 30° (inset in fig 1B1), containing 12 radiating black and white sectors, was rotated at velocities of 3, 5, 8, 10, 15, and 20˚/s applied in random order. Torsional OKN was recorded from subjects 1, 2, 3, 4, 5, 6, 7, and 8.

Stage 2: A sinusoidal grating pattern of cycle size 30° was rotated at velocities of 20, 40, 60, 80, 100, and 120˚/s applied randomly and tOKN was recorded from subjects 1, 3, 9, 10, 11, 12, 13, and 14.

Stage 3: A sinusoidal grating pattern of cycle size 90° (inset in fig 1Biii), containing four black and white sectors, was rotated at 20, 40, 100, 200, 400, 800, and 1000˚/s in random order, recording from subjects 1, 3, 5, 15, 16, 17, 18, 19, and 20. The larger cycle size was used for faster angular velocities to limit counter-rotational stimulus projection effects and ensured good stimulus visibility by all subjects.

The subject was asked to fixate the centre of the stimulus binocularly and not to focus on any particular point of the stimulus. Each stimulus was presented for a period of 30 seconds followed by a blank phase of 15 seconds consisting of a black screen during which the subject was asked to continue to centrally fixate the stimulus.

Figure 2: Mean slow phase velocity (median plus or minus quartiles) of all subjects in relation to the log of the stimulus velocity for stimulus velocities ranging from 3˚/s to 120˚/s at a cycle size of 30° (lefthand plots), and stimulus velocities ranging from 20˚/s to 1000˚/s at a cycle size of 90° (righthand plots), to clockwise and anticlockwise stimulation.

Figure 2: Mean slow phase velocity (median plus or minus quartiles) of all subjects in relation to the log of the stimulus velocity for stimulus velocities ranging from 3˚/s to 120˚/s at a cycle size of 30° (lefthand plots), and stimulus velocities ranging from 20˚/s to 1000˚/s at a cycle size of 90° (righthand plots), to clockwise and anticlockwise stimulation.
12.4°, 24.9°, 35.1°, 43.2°, and 50.8° diameter (inset in fig 3A), in random order and TOKN was recorded from subjects 1, 2, 3, 4, 5, 6, 9, and 12. To assess varying degrees of peripheral stimulation on the TOKN response, an artificial central scotoma (black round spot) was incorporated into a sinusoidal grating pattern of cycle size 90° and diameter 50.8°. The occluder sizes were 2.86°, 6.2°, 12.4°, 24.9°, 35.1°, and 43.2° (inset in fig 4A) presented in random order and TOKN was recorded in the same subjects as in the central stimulation experiment. A response box was used by the subjects to indicate when they “filled-in” the missing central portion of the stimulus (Cambridge Research Systems, Rochester, UK). All tests consisted of a 30 second binocular stimulation period followed by a blank phase during which the subject was asked to stare straight ahead as in experiment 1. The horizontal and vertical eye position was monitored to ensure the subject was viewing the centre of the stimulus in both experiments. The effects of central and peripheral stimulation were measured at velocities of 40°/s and 400°/s.

Data analysis

The quality of the torsional eye movements depends on the visibility of the reference segment of the iris selected at the beginning of the trial and is given by the “Strabs” system for each torsional sample. Only data that exceeded torsional quality of 0.5 were used for analysis. Velocity traces of the torsional data were generated using a simple three point differentiator filter. A velocity threshold of 10°/s was used to determine saccades in the torsional recording. The mean velocity over a minimum of 10 slow phases from each 30 second trace was used to give the mean slow phase velocity (MSPV) for each stimulus. The gain value was then calculated by dividing this MSPV value by the stimulus velocity. Since the mean slow phase velocities and gains were not normally distributed across the subjects, medians and quartiles were used. For experiment 2, MSPV and gain values were calculated during periods of filling-in and during periods of no filling-in for three subjects.

RESULTS

Experiment 1: the effect of stimulus velocity on TOKN gain

Figure 1A shows original eye movement recordings obtained in one representative subject. Figures 1Ai, ii, and iii show original recordings obtained at 3°/s, 8°/s, and 20°/s, respectively. While there is a minimal TOKN response at 3°/s, a clear response is demonstrated at 8°/s and 20°/s. Only two out of eight subjects exhibited a visible TOKN response at 3°/s in the clockwise direction and one subject displayed a response in the anticlockwise direction.

Figure 1B shows median gains across all tested stimulus velocities. The largest gain occurred at 8°/s velocity in both clockwise and anticlockwise directions (fig 1Bi). Between the stimulus velocities 8°/s and 20°/s, the median gain remained fairly stable varying from 0.16 to 0.10 and 0.13 to 0.12 for clockwise and anticlockwise stimulation respectively. When stimulus velocity was increased from 20°/s to 120°/s, the median gain fell to 0.03 and 0.02 for clockwise and anticlockwise stimulation respectively (fig 1Bii). At stimulus velocities from 20°/s to 1000°/s the gain fell from 0.075 to 0.002 and 0.073 to 0.0019 for clockwise and anticlockwise stimulation (fig 1Biii). There was no difference in gain between the 30° and 90° cycle size stimuli, which were both tested at velocities of 20°/s, 40°/s, and 100°/s.

The MSPV increased as stimulus velocity increased up to 200°/s achieving a maximum MSPV of approximately 3°/s in both directions (fig 1Bii). Between the stimulus velocities 8°/s and 20°/s, the median gain fell to 0.03 and 0.02 for clockwise and anticlockwise stimulation respectively (fig 1Bii). At stimulus velocities from 20°/s to 1000°/s the gain fell from 0.075 to 0.002 and 0.073 to 0.0019 for clockwise and anticlockwise stimulation (fig 1Biii). There was no difference in gain between the 30° and 90° cycle size stimuli, which were both tested at velocities of 20°/s, 40°/s, and 100°/s.

The MSPV increased as stimulus velocity increased up to 200°/s achieving a maximum MSPV of approximately 3°/s in both directions (fig 2). For a cycle size of 30° (see lefthand plots of fig 2), the response commenced at 3.4°/s velocity for clockwise stimulation and 3.3°/s velocity for anticlockwise stimulation (intercept with the x-axis). The MSPV was linearly correlated with the log of the stimulus velocity increasing by 2°/s per log unit up to the maximum stimulus velocity used of 120°/s ($r^2 = 0.95$ for clockwise stimuli and 0.93 for anticlockwise stimuli). For a cycle size of 90° (righthand plots of fig 2), the MSPV increased by approximately 1.5°/s per log unit increase from 20°/s to 200°/s. Above 200°/s, however, the MSPV began to tail off, decreasing to a MSPV of approximately 2°/s for the maximum stimulus velocity used of 1000°/s. For all velocities, there was no difference between clockwise and anticlockwise stimulation.

Figure 3 (A) Original recordings of the right eye in one representative subject showing the effect of increasing stimulus field size. The stimulus is rotating in the clockwise direction. (B) Median torsional optokinetic nystagmus gain (plus or minus quartiles) of all subjects in response to increasing stimulus field size with the stimulus rotating at 40°/s (i) and 400°/s (ii) in the clockwise direction.
Experiment 2: the effect of stimulus area on tOKN gain

Figures 3Ai and ii show original recordings obtained using a stimulus size of 2.86° and 50.8° at 40°/s clockwise stimulation. The response to the 50.8° stimulus is much bigger than the response to the 2.86° stimulus. Figure 3Bi shows that the smallest field size of 2.86°, rotating at 40°/s evoked only 10% (0.0054) of the gain elicited by the largest field display (0.054) of 50.8°. Similarly, at 400°/s (fig 3Bii) the gain elicited by the smallest field size was 29% (0.0015) of the gain obtained by the largest stimulus (0.0052). Figure 4Ai and ii show original recordings obtained with the smallest (2.86°) and largest central occlusion (43.2°) showing the tOKN response to be present even when 85% of the stimulus was occluded (fig 4Aii). Figure 4Bi and ii illustrate the effect of increasing central occluder size on median tOKN gain at the two different stimulus velocities used. At 40°/s (fig 4Bi), when the largest central black spot occluded 85% (43.2°) of the 50.8° display, the gain was half (0.03) of the gain evoked when no central occluder was used (0.06). At 400°/s (fig 4Bii), using the largest central occluder, the gain was 17.5% (0.0014) of the gain evoked without any central occlusion (0.008).

During central occlusion experiments several subjects reported filling-in of the centrally occluded area by perceiving the continuation of the stripes of the stimulus into the occluded area. The perception of filling-in was changeable with some subjects constantly perceiving filling-in and others fluctuating between filling-in being present and absent within the 30 second period of stimulation.

Figure 5A shows a sample eye movement recording trace where filling-in and no filling-in are indicated during the same period of stimulation. There are no differences in waveform during the two conditions.

Three subjects were examined who showed both filling-in and non-filling-in for the same stimulus to investigate whether this perception had any effect on the eye movements generated. The central occlusion experiments were repeated three times in the three subjects at a stimulus velocity of 40°/s. Figure 5B shows the tOKN gains during filling-in and none filling-in periods of peripheral stimulation in all three subjects. All subjects consistently demonstrated a filling-in response at the smaller sized central occluders of 2.86°, 6.2°, and 12.4°. There was no visible difference in tOKN gain during filling-in and non-filling-in periods.

DISCUSSION

This study has shown, for the first time, that tOKN mean slow phase velocity (MSPV) is linearly related to the log of the stimulus velocity, with no difference in clockwise and anticlockwise stimulation. We have also shown that a significant proportion of the tOKN response is due to peripheral field stimulation, in contrast with a previous report, which states that the response is dependent mainly on central field stimulation. When central areas of the stimulus were occluded subjects reported “filling-in” but this did not influence the tOKN response.

The maximum gain occurred in response to 8°/s stimulation with median values of 0.16 and 0.13 in clockwise and anticlockwise directions, respectively. Previously reported values using similar stimulus velocities differ greatly. Collewijn et al. reported a very low gain value of 0.035 to 0.058 tOKN stimulation in two subjects with highly variable results. In contrast, Morrow et al. reported a higher gain of 0.22 in response to 10°/s stimulation. This disparity may be due to differences in the stimuli used, since a random dot pattern was employed by Collewijn et al., whereas radiating stripes, similar to that used in the present study, were used by Morrow et al. In previous papers, studies employing a random pattern stimulus to elicit tOKN tend to show peak gain of less than 0.1, whereas those using radiating stripes of various forms, with the exception of one study, report peak gain responses of 0.1 or greater.

Our results also demonstrate a measurable tOKN response at the higher range of stimulus velocities, with stimuli rotating as fast as 1000°/s achieving a gain of 0.002 and 0.0019 for clockwise and anticlockwise directions, respectively. It was also interesting to note that the MSPV increased as stimulus velocity increased up to 200°/s achieving a maximum MSPV of approximately 3°/s in both directions. Previous papers have not used a large enough range of stimulus velocities to establish the peak response stimulus velocity. It is possible that the excessive linear velocities generated at the periphery of the faster rotating stimuli limit any further increase in the tOKN MSPV response.
There are two competing mechanisms involved in the generation of horizontal and vertical OKN. In humans, a pursuit mechanism is thought to dominate the OKN response, which has a rapid build up time and relies upon foveation. A delayed OKN system also contributes to human OKN, especially at higher stimulus velocities, but builds up more slowly and is generated by peripheral vision. Accordingly, horizontal and vertical OKN gains approach 1 at lower stimulus velocities, but become low and irregular at stimulus velocities of 80–90˚/s for horizontal OKN, and 60˚/s for vertical OKN. Torsional OKN is not influenced by a pursuit mechanism since little or no target movement takes place at the fovea when the subject fixates on the target centre. Consequently, torsional OKN, which is probably dominated by the peripheral field, exhibits low OKN gains at a wide range of stimulus velocities.

In our experiments, the smallest field size (2.86˚) display evoked only a small proportion of the gain (10% at 40˚/s) elicited by the largest field stimulus (50.8˚). We also have demonstrated that when a large amount (85%) of the central field was occluded, a considerable amount of the tOKN gain was retained (50% at 40˚/s). The only previous study investigating the effects of central and peripheral stimulation on the tOKN response concluded that tOKN was preferentially stimulated using central stimuli. This was based on the assumption that when the central 75˚ of their display was occluded, only 30% of the full field tOKN response was maintained. In the central visual field, the rod free foveal region is approximately 1.25˚. Hence, occlusion of 75˚ also includes a significant amount of the peripheral field. The importance of the peripheral field for the tOKN response may be related to the degree of linear retinal slip, which increases with eccentricity for tOKN stimuli, in contrast with horizontal and vertical OKN stimuli. Greater retinal slip may also explain the more rapid drop-off in gain with increasing occluder size when using the faster stimulus velocity (400˚/s). Linear velocities may become excessive at the periphery at this velocity causing a drop off in the tOKN response.

Subjects in our study perceive a completion of the peripheral stimulus into the centrally occluded area, which was more apparent when the smallest sized central occluders of 2.86˚, 6.2˚, and 12.4˚ were used. This process of “filling-in” causes visual stimuli to be perceived as arising from an area of the visual field where there is no actual visual input. Filling-in of the peripheral stimulus did not have any measurable effects on the eye movements generated. This perception of filling-in has not been previously described for tOKN stimuli. However, Valmaggia et al.13 have described a filling-in response occurring during horizontal OKN in patients with central scotomas of 15˚, 18˚, and 16˚. This filling-in elicited OKN whereas OKN was not present when there was no filling-in. The authors suggested that the ability of filling-in to directly effect eye movements is the result of motion sensitive areas of the visual cortex being stimulated through the active neural adaptation processes triggered during filling-in.

In conclusion, we have demonstrated that a large range of stimulus velocities can elicit torsional optokinetic nystagmus, and that tOKN mean slow phase velocity is linearly related to the log of the stimulus velocity. We have also demonstrated that peripheral field stimulation provides a significant contribution of the tOKN response and that filling-in of torsional stimuli does not affect the eye movements generated.

Of further interest would be to study the effect of pathological central scotomas on tOKN and also conditions where it has been previously demonstrated that asymmetries of monocular horizontal and vertical OKN response are caused by impairment of early visual development—for example, congenital squint syndrome.

ACKNOWLEDGEMENT
We thank the National Eye Research Centre (NERC).

Authors’ affiliations
S J Farooq, F A Proudlock, I Gottlob, Department of Ophthalmology, University of Leicester, Robert Kilpatrick Clinical Sciences Building, Leicester Royal Infirmary, PO Box 65, Leicester LE2 7LX, UK

REFERENCES


