

M. R. Ibbotson · N. S. C. Price · V. E. Das ·
M. A. Hietanen · M. J. Mustari

Torsional eye movements during psychophysical testing with rotating patterns

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Abstract Torsional eye movements were measured while subjects viewed a large, high contrast windmill pattern rotating at 53°/s or a small (5° diameter) dot pattern rotating at 115°/s. Both stimuli generated rotational eye movements consisting of torsional optokinetic nystagmus (tOKN) superimposed on a slow torsional drift in the direction of pattern rotation. With the wide-field windmill stimulus, torsional drifts of up to 7° over 20 s were found. The dot pattern produced drifts of up to 2° over 5–20 s. In both cases, the slow-phase speeds during tOKN were low (0.5–1°/s). We conclude that reductions in slip speed are minimal with rotating stimuli, so torsional eye speeds will have a minimal effect on investigations of rotational motion aftereffect strength and perceived speed. While the slow-phase tOKN gain is low, the slow drift in torsional eye position will have significant effects on psychophysical results when the tests rely on keeping selected regions of the stimulus confined to specific areas of the retina, as is the case for phantom or remote motion aftereffects.

Keywords Ocular torsion · Motion aftereffect · OKN · Phantom MAE · Global motion

Introduction

Psychophysical investigations of motion processing using complex motion have found differences in the effects of rotational, radial and translational motion. Radial motion is perceived as moving faster than rotation or translation (Geesaman and Qian 1996, 1998; Bex and Makous 1997; Clifford et al. 1999), while motion aftereffects (MAE) are

stronger for radial and rotary motion than for translation (Bex et al. 1999). Further, remote or phantom motion aftereffects, which are MAEs generated in regions of the visual field that are adjacent but not covered by the adapting pattern (von Grunau and Dube 1992; Price et al. 2004), tend to be larger for radial and rotary motion than for translation (Snowden and Milne 1997; Bex et al. 1999). It is not clear if eye movements contribute to the effects observed in these experiments.

When viewing translation, the presence of a fixation spot significantly reduces translating eye movements (Dichgans and Jung 1969; Barnes and Crombie 1985). In contrast, viewing rotation in the fronto-parallel plane generates rotation of the eye about the line of sight (Crone 1975; Howard et al. 1994; Howard and Rogers 1995). These torsional eye movements display optokinetic nystagmus (tOKN): slow-phase rotations in the direction of the stimulus interspersed with rapid counter-directed saccades. The speed of the slow-phase rotations is dependent on the stimulus size and rotational speed, and the baseline torsional eye position can change by $\pm 5^\circ$ during a 30 s stimulus period (Howard et al. 1994; Farooq et al. 2004). This suggests that torsional eye movements could affect the interpretation of psychophysical studies of complex motion in two ways. Firstly, it could reduce rotational retinal slip speeds, thus reducing the perceived speed and the rotational MAE when viewing rotating patterns (Seidman et al. 1992). Secondly, in phantom MAE studies, test and adapting regions are typically juxtaposed but are not meant to overlap. Baseline changes in torsional eye position could corrupt this separation by rotating supposedly unadapted regions of the retina into the stimulus adapting region. The aim of this paper is to investigate if torsional eye movements could affect the outcome of typical psychophysical tasks.

Methods

Five subjects with no history of oculomotor abnormalities participated in these experiments and provided informed

M. R. Ibbotson (✉) · N. S. C. Price · M. A. Hietanen
Visual Sciences, Research School of Biological Sciences,
Australian National University,
2601, Canberra, Australia
e-mail: ibbotson@rsbs.anu.edu.au

M. R. Ibbotson · V. E. Das · M. J. Mustari
Visual Sciences Division, Yerkes National Primate Center,
Emory University,
Atlanta, USA

consent following Emory University's IRB protocol. All stimuli were generated using a VSG2/5 graphics card (CRS Ltd.) and projected onto a 1.7×1.7 m screen (NEC Multisync LT140, 100 Hz frame rate, 1024×768 pixels) viewed at 1 m. Eye positions were sampled in three dimensions at 1 kHz with two orthogonal magnetic fields (CNC Engineering) and a double loop search coil on one eye (Skalar Medical, Delft, Netherlands). Eye velocities were subsequently calculated using a central difference algorithm. A topical anaesthetic (Proparacaine HCl 0.5%, Ophthatic, Allergan, Irvine, USA) applied to the eye with the search coil reduced the ability of the eye to focus, so subjects viewed the stimuli monocularly through the free eye, with all measured eye movements presumed conjugate (Van Rijn et al. 1994).

Our stimuli were a rotating windmill and a dynamic visual noise stimulus (DVN) used previously to study motion aftereffects (Snowden and Milne 1997). A two-pixel red fixation spot was placed at the centre of both stimuli. The windmill pattern (Fig. 1B, inset) subtended 100° at the eye and consisted of eight alternate black and white segments of 45° arc and 100% Michelson contrast, rotating at 53°/s (0.147 rev/s).

The DVN stimulus consisted of a bright background containing 400 dark dots uniformly distributed within a circular aperture of 5° diameter (Fig. 1E, inset). Individual dots lasted for 80 ms before being replotted at random locations elsewhere in the aperture. The rotation speed of the dots was 115°/s. To replicate the protocol of Snowden and Milne, each DVN trial began with a 60 s adaptation phase of coherently rotating dots. This was followed by 48 test phases lasting 0.5 s alternating with top-up adaptation phases lasting 6 s. Dot coherence in the adaptation phases was 100%, meaning that all dots rotated in the same

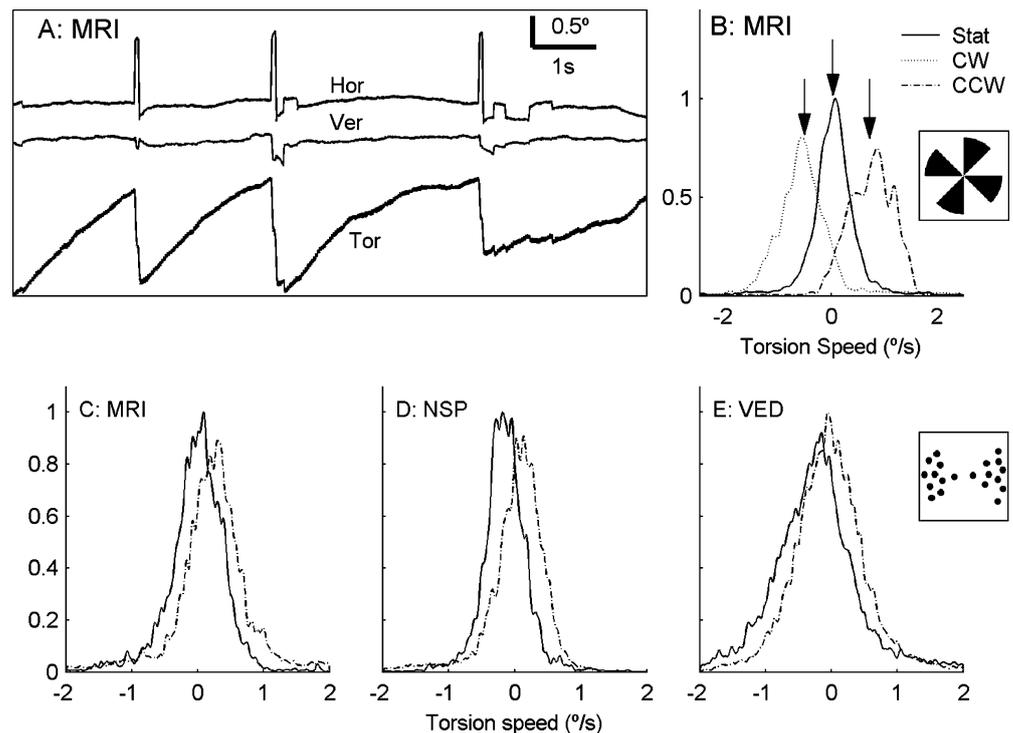
direction. Dot coherence in the test phases was randomly varied from 96% coherence in one direction, through 0% (random motion), to 96% coherence in the other direction. The percentage coherence indicates the proportion of dots moving with true rotational trajectories. The remaining dots move in random directions, with speeds appropriate for their positions relative to the fixation spot. During the adapting phases of stimulation, the moving dots were presented in two quadrants centred on the horizon. During test phases, dots were only presented in the unadapted vertical quadrants, giving no physical overlap of the adapt and test regions. Following each test phase, the screen went grey and subjects were asked to indicate the direction of perceived motion to generate a psychophysical measure of the strength of the MAE.

Results

Eye movements during windmill stimulation

For each stimulus condition we assessed changes in the horizontal, vertical and torsional eye position and speed over time. In all subjects, fixating the centre of a rotating windmill stimulus generated strong torsional optokinetic nystagmus (tOKN) consisting of slow-phases in the direction of stimulus rotation, followed by rapid counter-rotating torsional saccades (Fig. 1A). Each slow-phase lasted up to 3 s, during which the eye rotated up to 2°. The X-Y positions of the eye were very stable during the slow tracking phases of the tOKN, but small eye displacements (0.5–1°) sometimes occurred during the rapid torsional saccades. The point of fixation was within 0.10° for 75% of the time and 0.28° for 95% of the time.

Fig. 1A–E Eye movements when viewing rotation. **A** Horizontal, vertical and torsional eye positions during 10 s of viewing a windmill stimulus. **B** Normalised distributions of torsional eye speed during 10 s of viewing a windmill that is stationary (*solid line*), rotating CW (*dotted line*) and rotating CCW (*dash-dots*). (**C–E**) Histograms of torsional eye speed during 50 s of viewing a DVN stimulus that is stationary (*solid line*) or rotating CCW (*dash-dots*)



For subject MRI, the slow-phase tOKN speeds while viewing a blank stationary background show an approximately normal distribution centred about zero, with 95% bounds on torsion speed of $\pm 0.80^\circ/\text{s}$ (solid line: Fig. 1B). During clockwise and counter-clockwise rotation of the windmill stimulus, the median torsion speeds during the entire period of rotation were $-0.55^\circ/\text{s}$ and $0.77^\circ/\text{s}$, respectively (arrows in Fig. 1B). The torsional eye speeds associated with the counter-directed saccades are outside the range of the histograms and are not shown. The slow-phase gain of tOKN (eye speed/windmill rotation speed) for subject MRI was very low (0.010 for CW rotation; 0.015 for CCW rotation). Similar slow-phase gains ranging from 0.006 to 0.017 were obtained for all five subjects, in agreement with previous studies using similar stimulus speeds but no fixation spots (Seidman et al. 1992; Suzuki et al. 2000).

Eye movements during the DVN stimulus

The DVN stimulus generates tOKN with individual slow phase components lasting up to 3 s. These typically rotate the eyes by $<0.3^\circ$ but up to 0.6° . Thus the DVN stimulus had the same effects as the windmill stimulus, but produced smaller torsional eye movements. Horizontal and vertical eye positions were stable throughout fixation. Two subjects maintained fixation within 0.21° for 95% of the time; the remaining three subjects had 95% positional bounds of 0.2° in one plane and 0.4° in the other plane.

Figure 1C–E shows normalised distributions of tOKN speed for three subjects during 50 s of fixation. When viewing a stationary control pattern (solid line), the median speeds were either at (subject MRI) or slightly below zero (subjects NSP and VED). During counter-clockwise rotation of the DVN stimulus, the median torsional eye speed increased to values greater than zero (dotted line) while clockwise rotation generated similar sized shifts of the mean torsional eye speed but in the negative direction (data not shown). For all five subjects, torsional positions and speeds when viewing the rotating DVN stimulus were significantly different from those measured when viewing stationary controls (Wilcoxon rank sum test, $p < 0.05$). Finding the median torsion speed in the first 10 s of rotation rather than during a 50 s time period did not produce systematically different results. The mean shift in eye speed for all five subjects tested with the rotating DVN stimulus was $0.2^\circ/\text{s}$. The rotation speed of the DVN pattern was $115^\circ/\text{s}$, so the mean slow-phase gain of tOKN was $0.2/115 = 0.0017$, or less than 0.2%.

Slow rotational drift

With the windmill and DVN stimuli, subjects showed a slow torsion in the direction of the moving pattern, beginning as soon as the stimulus started to rotate and lasting for 5–20 s (Fig. 2). The nystagmic beats of the more short-lived tOKN were superimposed on this slow

rotational drift, giving a slow cumulative change in torsional position. Arrows in Fig. 2 indicate the duration and size of the initial torsional drift for subject VED, who showed rotations of approximately 7.5° over 10 s with CW motion and 5.5° over 5 s with CCW motion. Once the stimulus stopped rotating the eye returned close to the starting position. Averaged across the five subjects, this initial drift averaged $3.8^\circ \pm 3.0$ (SD) for the windmill stimulus and $1.2^\circ \pm 1.3$ for the DVN stimulus.

During rotation of the DVN stimulus, the slow drift was not as large but it was still evident. Figure 2C shows the torsional eye position during the 60 s adaptation period and six test phases of the psychophysical protocol using DVN. The eye rotated 2° in the first 20 s of the adaptation phase, shifting unadapted regions of the retina into regions of the stimulus where motion was present. When the stimulus changed from the adaptation to the test phases (vertical dashed lines, Fig. 2C), the eye rotated opposite to the adapting stimulus rotation. As soon as the 6 s top-up adaptation began, the eye would again rotate by up to 1° in the direction of the stimulus motion. This change in eye torsion position with each change in stimulus condition was present for all five subjects. Therefore, during top-up adaptation the boundaries of the designated adapting and non-adapting regions of the retina periodically overlapped.

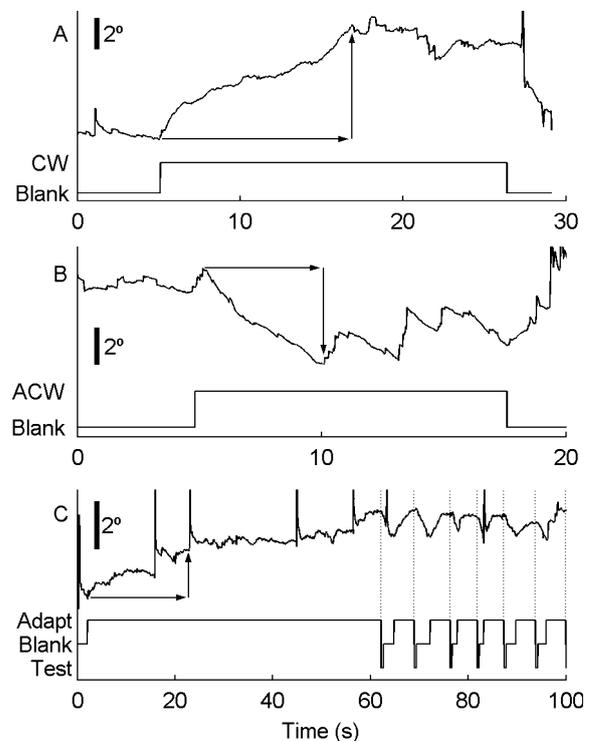


Fig. 2A–C Slow drift in torsional position for a windmill rotating CW (A) and CCW (B), and a DVN stimulus rotating clockwise (C). The lower trace in A and B shows when the pattern was visible. The stimulus trace in C shows the adaptation phase followed by alternating test (lowest level), blank subject response period (middle level) and adaptation phases. Vertical dotted lines mark the end of each adaptation phase. Arrows indicate the duration and extent of the torsional eye drift

Discussion

The aim of this study was to examine the eye movements that occur when viewing small rotating patterns, as used in many psychophysical experiments. Our results can be summarized into three points. Firstly, horizontal and vertical eye movements are minimal when fixating the centre of a small rotating pattern. Secondly, a small rotating DVN stimulus (5° diameter) is sufficient to drive tOKN, which implies a significant drive from the fovea. Thirdly, when viewing a rotating stimulus, the torsional eye position can drift by over 5° into a new steady-state position.

Effects of eye torsional speed

Our results with the large windmill stimulus support previous findings that torsional eye movements have little influence on the rotary slip speed on the retina (Seidman et al. 1992). We have also shown that with small stimuli and high stimulus speed, eye torsion speeds are very low, reducing the slip speed on the retina by less than 0.2%. Thus they are unlikely to have significant effects on psychophysical tests of perceived speed. However, with slower rotation speeds and large stimuli, slow-phase tOKN gains as high as 0.15 can be induced (Howard et al. 1994; Farooq et al. 2004), suggesting that care must be taken in psychophysical tests using larger stimuli.

Effects of eye torsional position

We found shifts in the baseline torsional eye position during the initial period of stimulus rotation, with a rapid return to the initial eye position when rotation stops. Similar rotational shifts of $3\text{--}4^\circ$ when viewing a large windmill pattern have been reported previously (Seidman et al. 1992). These slow drifts are unlikely to be caused by coil slippage because they are correlated with stimulus onset and offset and saccades in the X-Y plane were consistently small (Bergamin et al. 2004). It is possible that large torsional shifts could lead to low tOKN gains because the eyes simply cannot rotate further. However, comparison of tOKN gains while viewing the first 10 s of rotation and a longer 50 s period of rotation showed no significant differences.

Our results show that tOKN does occur when subjects view the DVN stimulus despite its small diameter (5°). Subjects did not move their eyes by more than $\pm 0.4^\circ$ in the X-Y plane during stimulation, and in fact most fixation errors were $< 0.2^\circ$. This is probably not sufficiently large to affect psychophysical results. During the tOKN the eyes significantly rotated in the torsional plane by up to 7° with

the windmill stimulus and 2° with the DVN stimulus. These torsions were sufficient to expose regions of the retina that were not supposed to be adapted to the adapting segments of the stimulus. This could have an influence on phantom MAE studies in which adapting and test regions are juxtaposed but ideally nonoverlapping (Snowden and Milne 1997; Bex et al. 1999). Consequently, we recommend that a gap of at least 5° of arc between adapting and test regions is required in experiments exploiting phantom MAEs to study complex motion processing in humans.

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