Effect of distance upon horizontal and vertical look and stare OKN

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Previous reports suggest that distance influences horizontal stare OKN gains; however, the effect of distance on vertical OKN and look OKN is unknown. Horizontal and vertical look and stare OKN gains were recorded in 16 healthy volunteers (velocity 38.4°/s) at three distances (0.3 m, 1 m, and 2.5 m) and two different stimulus sizes. Asymmetry of responses and correlation of gains in different directions were compared. Measurements at near were compared with and without glasses. Distance did not significantly affect horizontal look and stare OKN or vertical look OKN, however, downward stare OKN gains were reduced at greater distances (p = 0.002). Mean downward stare OKN gains recorded in each individual were strongly correlated to leftward and rightward gains but not upward gains. In contrast, upward OKN gains were not correlated to gains in leftward, rightward, or downward directions. Downward stare OKN responses are significantly sensitive to the effects of distance, whereas stare OKN in other directions and look OKN responses in all directions are not. Individual mean downward stare OKN gains are more closely related to horizontal responses rather than upward responses. This suggests that the downward OKN system is more functionally related to the horizontal system rather than the upward OKN system.

Keywords: optokinetic nystagmus, distance, human, vertical asymmetry, oculomotor


Introduction

Optokinetic nystagmus (OKN) is a type of eye movement that stabilizes images on the retina during global movement of the visual field. It consists of alternating slow tracking movements followed by rapid recovery fast phases. The quality of the image stabilization depends on the gain of the OKN, the velocity of the slow phase divided by the velocity of the stimulus (gain = 1 is optimal retinal stabilization). Two forms of OKN have been described (Ter Braak, 1936). Look OKN (sometimes called pursuit OKN) consists of voluntarily tracking details in the moving visual field and usually resulting in high gain, large amplitude OKN. Stare OKN is a reflexive response that occurs when passively following a moving visual field and has a lower gain with smaller amplitude slow phases (Hainline, Lemerie, Abramov, & Turkel, 1984; Lott & Post, 1993).

There is a consensus in the literature that horizontal OKN is relatively symmetrical in healthy human subjects with similar gains in the temporalward and nasalward directions. There is less clarity, however, concerning the symmetry of vertical OKN with the majority of reports describing preference for upward stimuli (Clément & Latham, 1991; Garbutt et al., 2003; LeLievre & Correia, 1987; Ogino, Kato, Sakuma, Takahashi, & Takeyama, 1996; Takahashi, Sakurai, & Kanzaki, 1978; van den Berg & Colliewijn, 1988), but others describing preference for downward stimuli (Schor & Narayan, 1981) and others describing no asymmetry at all (Baloh, Richman, Yee, & Honrubia, 1983; Collins, Schroeder, Rice, Mertens, &
Kranz, 1970; Hainline et al., 1984). The issue is further confounded by the fact that symmetry of vertical OKN is dependent on several visual and vestibular influences such as the degree of central and peripheral field stimulation (Murasugi & Howard, 1989b) and the direction of gravity with respect to the head (Bohmer & Baloh, 1990; Clément, 2003). Recently, Knapp, Gottlob, McLean, and Proudlock (2008) have described that healthy individuals show a particular propensity for vertical OKN asymmetry (which can be either upward or downward preference or symmetrical), which remains relative consistent despite viewing conditions. The reason for this is unknown.

The effect of distance on OKN has been underexplored. To our knowledge only one study has systematically explored the effect of distance on horizontal OKN. Jagla (1978) compared four distances (0.5, 1.0, 1.5, and 2.0 m) in 20 subjects and found the OKN gain to decrease for the closest distances (only the rightward direction was tested). The effect of distance on vertical OKN has not been investigated and in particular the effect of distance on the asymmetry of vertical OKN.

Functionally, OKN responses in humans are most commonly generated from global motion caused by locomotion through space, i.e., walking and running in humans. The relationship between vertical OKN and distance is an interesting question since, during natural locomotion, objects in the lower visual field tend to be closer in proximity than in the upper visual field. If anything, when we move through space, the velocity of downward motion in our visual field is more closely related to horizontal motion rather than upward motion. Recently, Yang, Zhu, Kim, and Hertle (2007) have shown that powerful horizontal vergence and vertical version OKN responses occur when viewing grating patterns moving in the ground plane under monocular conditions. These results indicate that optokinetic responses can be modulated by perceived proximity alone rather than being driven by binocular disparity cues.

We have explored the effect of distance on both horizontal and vertical OKN investigating both look and stare OKN and specifically looking at the effect of distance on vertical asymmetry. Three different distances and two different stimulus sizes were compared (only one size could be used for the furthest distance), matching stimulus parameters such as visual angles and contrast. Measurements at near were made with and without glasses to explore possible confounding affects of accommodation. We have also compared vertical OKN responses in individuals with horizontal OKN given the functional differences in vertical OKN caused by global motion as described above.

**Methods**

Sixteen healthy volunteers (4 males, 12 females, mean age 31.2 years, SD 5.8 years) with no known history of ophthalmological, neurological, or otological abnormality were recruited to the study. An orthoptic examination was performed on all volunteers to exclude amblyopia, binocular vision defects, or any underlying ocular motility problems. All volunteers had a best corrected visual acuity of 0.0 logMAR or better in each eye (difference between eyes ≤ 1 logMAR line) and achieved binocular vision of 60 s of arc or better using TNO test for stereoscopic vision (Richmond Products, Albuquerque, NM). Contact lenses were used to correct refractive error in 4 patients. All other subjects were emmetropic for distance. 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.

The OKN stimulus was projected onto a rear projection screen (1.75 m width and 1.17 m height) using an Epson EMP-703 (resolution 1024 × 768, frame rate 60 Hz) driven by a calibrated high-resolution video card (VSG 2/5, Cambridge Research Systems, Rochester, UK; DAC output resolution 15 bits per color). The setup was gamma-corrected using a photometer (OptiCAL, Cambridge Research Systems). The stimuli for all three distances tested (0.33 m, 1 m, and 2.5 m) consisted of a sinusoidally modulated contrast grating (spatial frequency = 0.26 cycles/degree; peak to peak contrast 93%; luminance from 0.45 to 12 cd m⁻²) moving at a linear velocity of 38.4°/s. Luminances were matched for different distances by varying the contrast and brightness on the projector using a radiometer (IL1700, R #106 radiance barrel, SEE038 detector, International Light, Newburyport, MS, USA) with a photopic filter that matches the CIE V(λ) photopic curve to measure the luminance. The stimulus was viewed binocularly and applied in four directions: upward, downward, leftward, and rightward. Look and stare OKN were recorded under the following conditions:

1. A larger stimulus of ±40° width and ±30° height was tested at 0.33-m and 1-m distances.
2. A smaller stimulus of ±10° width and ±7.5° height was tested at 0.33-m, 1-m, and 2.5-m distances.
3. Both larger and smaller stimuli at 0.33 m were tested with and without the addition of near vision glasses (n = 13) to compare the effects of accommodation on OKN.

Eye movements were recorded using a high-resolution pupil tracker at a sample rate of 250 Hz (EyeLink I, SensoMotoric Instruments, Berlin, Germany). The eye tracker has a resolution of 0.005° and a range of ±30° with a noise level of <0.01° RMS within this range (company specifications). The eye data were calibrated at each distance separately (and during glasses wearing) using 9 fixation points, projected individually in the shape of a 3 × 3 grid, ±16.54° wide and ±16.54° high. Eye tracker recordings were converted offline to Spike2 neurophysiological software system files for subsequent analysis (Cambridge Electronic Design, UK). Head movements
were minimized using a chin rest, although the EyeLink eye tracker provides head compensated gaze data.

Stimuli for each distance were presented in random order for a period of 20 s followed by a rest period of at least 15 s. When measuring look OKN, the subject was instructed to actively fix and follow individual OKN target stripes, whereas when examining stare OKN, the subject was encouraged to look toward the center of the screen while keeping the stripes in focus. Look OKN was delineated from stare OKN as having slow phases of duration >0.45 s. The justification for this is previously described in Knapp et al. (2008).

Mean slow phase velocity (MSPV) was calculated from the total distance traveled/total time taken during the slow phases. This method was used in preference to the mean of each slow phase velocity to prevent the measurement from being distorted by short, less consistent, slow phases. The gain was the ratio of MSPV/stimulus velocity. Asymmetry indices (AI) were calculated using the following equations (MSPV = mean slow phase velocity):

\[
\text{Vertical AI} = \frac{\text{upward MSPV}}{\text{upward MSPV} + \text{downward MSPV}},
\]

\[
\text{Horizontal AI} = \frac{\text{rightward MSPV}}{\text{rightward MSPV} + \text{leftward MSPV}}.
\]

In addition, mean beat frequency (the number of quick phases per second) was measured as the mean reciprocal of the time between successive quick phases uninterrupted by blinks. The mean position held during OKN was estimated from the mean of the horizontal and vertical positions at the beginning and end of each slow phase.

**Statistical analysis**

Linear mixed models were used to estimate the effects of distance and stimulus size on OKN gain and asymmetry index including interactions in the models (SPSS v11). Gains were transformed using natural logarithm to yield distributions that were more normally distributed. Coefficients of variation (%) were calculated to estimate both the between- and within-subject variabilities.

**Results**

Original recordings from a representative subject are shown in Figure 1 for all experimental conditions. As
previously described look OKN was characterized by two distinct waveforms with long duration slow phases and infrequent quick phases and short duration slow phases with frequent quick phases (Knapp et al., 2008). The short duration OKN cycles appear to be when volunteers attempt to “lock on” to the next stimulus stripe. The amplitude of the long duration slow phases was greater when following large field stimuli (80° × 60°) compared to when following small field stimuli (20° × 15°). Stare OKN was characterized by a typical saw-toothed waveform for all conditions.

The change in mean gain with distance is represented in Figure 2 for large field and small field stimuli. Distance had no significant effect on look OKN gains (where stimulus direction is rightward: $F = 0.54, p = 0.59$; leftward: $F = 0.16, p = 0.85$; upward: $F = 1.25, p = 0.29$; downward: $F = 1.15, p = 0.32$). Distance, however, significantly affected stare OKN gains when stimulus was moving in the downward direction (rightward: $F = 1.64, p = 0.20$; leftward: $F = 1.35, p = 0.27$; upward: $F = 1.97, p = 0.15$; downward: $F = 6.68, p = 0.002$). Stare OKN gain decreased with increasing distance when volunteers viewed downward moving stimuli.

Horizontal and vertical asymmetry indices are shown in Figure 3 for look and stare OKN. Distance had no significant effect on horizontal and vertical asymmetries for look OKN (horizontal asymmetry index: $F = 1.10, p = 0.33$; vertical asymmetry index: $F = 0.09, p = 0.91$) and for stare OKN (horizontal asymmetry index: $F = 0.18, p = 0.83$; vertical asymmetry index: $F = 0.84, p = 0.43$).
However, stare OKN vertical asymmetry index was sensitive to stimulus size ($F = 10.8, p = 0.002$). Look OKN vertical asymmetry index: $F = 0.58, p = 0.49$. Horizontal asymmetry index: $F = 0.03, p = 0.85$ for look OKN and $F = 0.10, p = 0.75$ for stare OKN.

This reflected the pattern observed for vertical stare OKN mean gains (see Figure 2) in which an upward preference was evident for the larger stimulus size and a downward preference for the smaller stimulus size. As previously described asymmetries were relatively consistent irrespective of distance and stimulus size with an individual tending to show a similar degree of upward preference (positive asymmetry index) or downward preference (negative asymmetry index) for all stimuli (Knapp et al., 2008). This was most obvious for stare OKN vertical asymmetry indices (Figure 3, right-hand graph). Look OKN asymmetry indices were more tightly distributed (more symmetrical) than stare OKN asymmetry indices. For vertical look OKN, the distribution of asymmetry indices was narrower for the larger stimulus size.

The addition of near vision lenses had no significant effect on look OKN gain (rightward: $F = 0.03, p = 0.87$; leftward: $F = 0.82, p = 0.37$; upward: $F = 0.98, p = 0.32$; downward: $F = 1.46, p = 0.23$), or stare OKN gain (rightward: $F = 0.11, p = 0.74$; leftward: $F = 3.6, p = 0.07$);

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**Scatter plots of mean log gain**

![Scatter plots of mean log gain](image_url)

*Figure 4. Correlations between mean log OKN gains averaged across all trials for each individual comparing different directions of stimulus movement.*
Mean log OKN gains were averaged across trials (without glasses) for each individual for stimuli moving in each direction. Correlations between each stimulus direction were performed for individual mean log OKN gains (Figure 4, with the $r^2$ values shown in Figure 5). For stare OKN gains a clear difference was observed between the strength of the correlation for downward and horizontal stimulus directions compared to the correlation for upward and horizontal directions. Downward gains were strongly correlated to both rightward ($r^2 = 0.77$) and leftward ($r^2 = 0.50$) directions. This is comparable to the correlation between rightward and leftward gains ($r^2 = 0.78$). In contrast there was little correlation between upward gains and rightward ($r^2 = 0.03$) or leftward directions ($r^2 = 0.09$). There was also little correlation between upward and downward gains ($r^2 = 0.00$). For look OKN the pattern was less clear. There was a strong correlation between horizontal directions (rightward versus leftward, $r^2 = 0.78$) and little correlation between vertical directions (upward versus downward, $r^2 = 0.05$). The correlation between horizontal and vertical directions was weak with no obvious difference between upward and downward correlations (down versus right: $r^2 = 0.43$, down versus left: $r^2 = 0.27$, up versus right: $r^2 = 0.23$, up versus left: $r^2 = 0.25$).

Mean beat frequencies were not influenced by distance although OKN beat frequencies for horizontally moving stimuli were quicker than those for vertically moving stimuli for look and stare OKN ($p < 0.05$). There were no differences in beat frequencies for leftward and rightward
moving stimuli or for upward and downward moving stimuli.

During OKN the eyes tended to be positioned in the orbit in the opposite direction to the movement of the stimuli (i.e., toward the newly appearing stimuli, Figure 6). This was less marked in response to downward moving stimuli and also rightward moving stimuli especially during stare OKN.

### Conclusions

We observe that distance had no effect on horizontal look and stare OKN gains but significantly affected stare OKN gain in the downward direction. Vertical look OKN and stare OKN in the upward direction was not dependant on distance. Stimulus size had a much greater effect on OKN compared to distance. All look and stare gains were significantly reduced when viewing the smaller stimulus size with the vertical gains being most greatly affected especially in the upward direction. This resulted in the asymmetry of vertical OKN significantly changing with stimulus size but not with distance. Asymmetry of vertical OKN responses was relatively consistent for each volunteer with the inter-subject differences accounting for much of the variability in vertical asymmetry in stare OKN. There was a striking difference between upward and downward directions when comparing mean stare OKN gains in individuals in the four directions. Downward stare OKN responses were strongly correlated with leftward and rightward responses. In contrast, upward OKN responses were not correlated to responses in either leftward, rightward, or downward directions. This distinction was not observed for look OKN.

Distance had no observed effect on vertical look OKN or upward stare OKN, however, downward stare OKN gain was sensitive to the distance tested, decreasing with increasing distance ($p = 0.002$). The sensitivity of the downward OKN to distance could be related to the function of OKN during forward locomotion and the radial optic flow patterns associated with forward locomotion. Because of the proximity of the ground, vertical movement tends to be greatest in the downward directions during forward locomotion since image motion is inversely proportional to viewing distance. Objects moving downward in the visual field also represent those most likely to confront an individual moving forward. Velocity of downward motion due to the proximity of the ground and ground-based objects may be accentuated further if the head is tilted down or during the fixation of ground-based objects below the horizon (Calow & Lappe, 2007). Interestingly movement in the lower visual field is associated with superior OKN responses compared to the upper visual field (Muraseg & Howard, 1989a). Recently, Yang et al. (2007) showed that grating patterns moving in the ground plane (using a computer monitor lying flat) generate a powerful horizontal vergence and vertical downward version OKN response in humans even when viewing under monocular conditions (Yang et al., 2007). The fact that vergence eye movements are generated in the absence of binocular disparity cues suggests that powerful pre-programmed OKN responses are responsible for stabilizing gaze when moving forward along the ground. Although radial optic flow patterns were not used in this study it is possible that the sensitivity of downward OKN responses to the distance of the OKN target are related to specialization of the visual system to downward optic flow motion during forward locomotion. It would be of interest to further investigate whether the sensitivity of the downward OKN response to distance is influenced by gravity.

The observation that distance had no effect on horizontal OKN is at variance with the findings reported by Jagla (1978) who found a small but significant difference in OKN gain in 20 subjects tested at 0.5 m compared to 1.5 m ($p < 0.001$) and 0.5 m compared to 2.0 m ($p < 0.01$) for stimuli moving in a rightward direction. The discrepancy may be explained by the different experimental setup used by Jagla in which the stimulus projector was placed above the head of the volunteer and moved nearer the projection screen when testing shorter distances. Consequently, luminance was not matched for different distances tested. In the setup used for this study a rear projection system was used and the luminance matched when the projection system was placed at different distances from the projector screen. In addition, Jagla used a different OKN stimulus, i.e., a square wave modulated contrast grating stimulus (width ratio 1:2, cycle size 5°) moving at 21°/s and covering a visual field of 1.35 × 1.4 m. We used a sinusoidally modulated contrast grating (cycle size 4.4°, image sizes 80° × 60° and 20° × 15°) moving at a linear velocity of 38.4°/s.

Vertical OKN asymmetry was not significantly related to distance. This stood in contrast to the effect of stimulus size, which affected all OKN gains, especially vertical OKN and most markedly the upward direction leading to a change in vertical asymmetry. The dependence of vertical asymmetry on relative amounts of central and peripheral field stimulation has been previously investigated by Muraseg and Howard (1989b). They found an upward OKN preference that was exaggerated by biasing stimulation of the peripheral retina and diminished by stimulation of the central retina. The present findings indicate that the vertical asymmetry of stare OKN is more sensitive to the degree of central and peripheral stimulation in comparison to look OKN.

In a previous study (Knapp et al., 2008) we recently observed that individuals typically show a particular propensity for vertical OKN asymmetry, which remains relative consistent despite viewing conditions. The reason for this is not yet clear. These findings are corroborated in the present study where the variability in vertical asymmetry between subjects is relatively high compared
to differences caused by distance or even stimulus size (Figure 3). Here we observed another interesting feature in relation to the idiosyncratic nature of OKN responses, i.e., that downward stare OKN responses are strongly correlated to horizontal responses whereas upward responses are not (Figure 4). Indeed, stare OKN responses in the upward and downward directions are not correlated at all. This may indicate that, functionally, the downward OKN system is more closely related to the horizontal system than the upward system. In relation to radial optic flow patterns during forward locomotion, the velocity of horizontal motion is more closely related to downward motion due to the proximity of the ground and ground-based objects (Figure 7). This may explain the close vertical proximity of the mean eye position during downward OKN to the vertical position during horizontal OKN (Figure 6).

It has been observed that the cerebellar flocculus inhibits inputs from the anterior semicircular canals, which generate upward drift of the eyes on stimulation but do not inhibit inputs from the posterior canals that generate downward drifts (Leigh, Das, & Seidman, 2002; Pierrot-Deseilligny & Milea, 2005). Damage or inhibition of the flocculus consequently leads to downbeat nystagmus where the eyes drift upward and corrective quick phases are made downward. Electrophysiological studies have also shown that floccular Purkinje cells preferentially discharge in response to downward and ipsiversive movements (Marti, Straumann, & Glasauer, 2005). One possibility is that slow upward drifts of the eyes associated with the vestibular-optokinetic system are under a dynamic flexible control mechanism, which can be adjusted to meet, for example, differing gravitational demands. We postulate that the level of inhibition may differ from individual to individual leading to the idiosyncratic nature of vertical asymmetry. This could also explain the lack of relation between OKN during upward stimulation compared to the other three directions.

In summary, we find downward stare OKN responses to be most sensitive to the effects of distance in comparison to the other directions. Look OKN responses were not significantly affected by distance. Individual mean downward stare OKN responses were correlated to horizontal responses whereas upward responses were correlated to neither the horizontal directions nor upward responses. This could be explained by the function of downward OKN in relation to radial optic flow, which may be more functionally related to the horizontal system because of the close proximity of the ground.

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