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Using VR to investigate the relationship between visual acuity and severity of simulated oscillopsia

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Abstract

Purpose: Oscillopsia is a debilitating symptom resulting from involuntary eye movement most commonly associated with acquired nystagmus. Investigating and documenting the effects of oscillopsia severity on visual acuity (VA) is challenging. This paper aims to further understanding of the effects of oscillopsia using a virtual reality simulation.

Methods: Fifteen right-beat horizontal nystagmus waveforms, with different amplitude (1°, 3°, 5°, 8° and 11°) and frequency (1.25 Hz, 2.5 Hz and 5 Hz) combinations, were produced and imported into virtual reality to simulate different severities of oscillopsia. Fifty participants without ocular pathology were recruited to read logMAR charts in virtual reality under stationary conditions (no oscillopsia) and subsequently while experiencing simulated oscillopsia. The change in VA (logMAR) was calculated for each oscillopsia simulation (logMAR VA with oscillopsia – logMAR VA with no oscillopsia), removing the influence of different baseline VAs between participants. A one-tailed paired t-test was used to assess statistical significance in the worsening in VA caused by the oscillopsia simulations.

Results: VA worsened with each incremental increase in simulated oscillopsia intensity (frequency x amplitude), either by increasing frequency or amplitude, with the exception of statistically insignificant changes at lower intensity simulations. Theoretical understanding predicted a linear relationship between increasing oscillopsia intensity and worsening VA. This was supported by observations at lower intensity simulations but not at higher intensities, with incremental changes in VA gradually levelling off. A potential reason for the difference at higher intensities is the influence of frame rate when using digital simulations in virtual reality.

Conclusions: The frequency and amplitude were found to equally affect VA, as predicted. These results not only consolidate the assumption that VA degrades with oscillopsia but also provide quantitative information that relates these changes to amplitude and frequency of oscillopsia.

Introduction

Oscillopsia is a symptom characterised by a visual perception that the world is in constant motion, resulting from involuntary eye movement. Oscillopsia is common with acquired nystagmus but is also reported in 39% of those with infantile nystagmus. [1] The relationship between the severity of nystagmus eye movement and visual acuity (VA) has previously been reported for those with infantile nystagmus, [2, 3, 4, 5] but the effect of oscillopsia on VA has seldom been studied. [6, 7, 8] The use of motorised mirrors facing acuity targets is a previous attempt. [8] This paper utilises recently available virtual reality (VR) technology to simulate oscillopsia using nystagmus waveforms to investigate the relationship between severity of oscillopsia and VA.

In the context of this study, VR technology refers to a headset incorporating a specially calibrated digital display to provide the wearer with stereoscopic vision in a virtual environment. The device incorporates head tracking capabilities which permit the display to be updated as the wearer rotates his/her head, providing an immersive experience. There are several VR devices on the market: ranging from dedicated headsets connected to high-performance computers (e.g. Oculus Rift), to smartphone-based headsets, which use the computational power and high-resolution display of a smartphone.

We have previously presented a representative simulation of oscillopsia in a VR smartphone app. [9] The VR simulation in this paper extends this to perform an inaugural quantitative investigation into the relationship between VA and severity of oscillopsia. Greater understanding of this relationship may allow both clinicians and patients to make more informed decisions regarding care and improve understanding of how the condition affects quality of life.

Methods

VR Simulation of oscillopsia

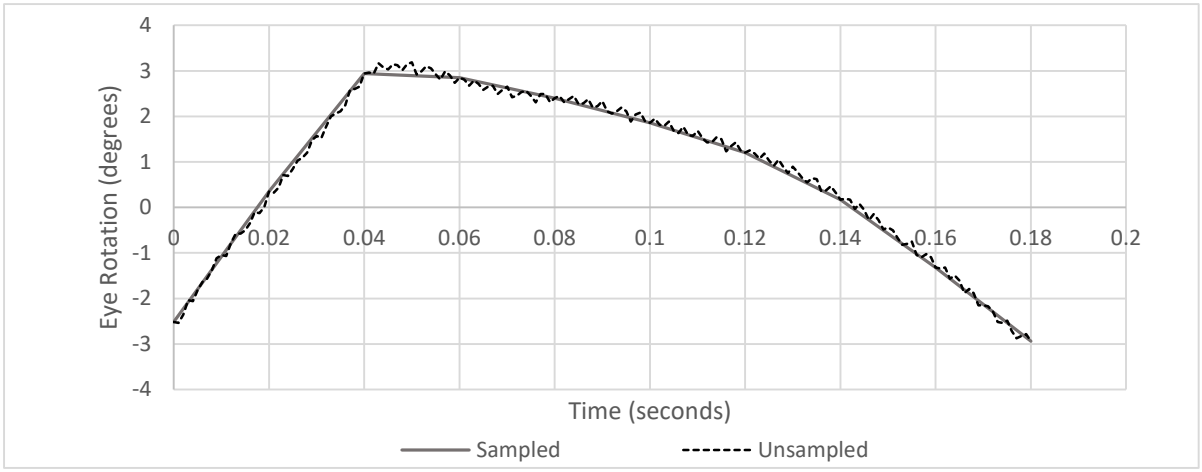
Our VR oscillopsia simulation app for smartphones (described in [9]), incorporated eye movement tracking data from nystagmus sufferers (tracked using an EyeLink 1000+). Eye rotation over time (in degrees) was calculated to produce a series of rotational coordinates every 0.02 seconds. The rotations were imposed onto two virtual cameras (or "virtual eyes") that provide the view presented to each eye in VR. With each 0.02s fixed frame the virtual eyes were moved to the proceeding rotational coordinates so the wearer of the VR headset could experience a realistic simulation of oscillopsia.

This current study uses the same method of simulation with approximated nystagmus waveforms. A single, complete phase of a right-beat horizontal jerk nystagmus waveform was adapted to generate a series of idealised waveforms of differing severity. The process used to create the artificial waveforms is described with the aid of Figure 1:

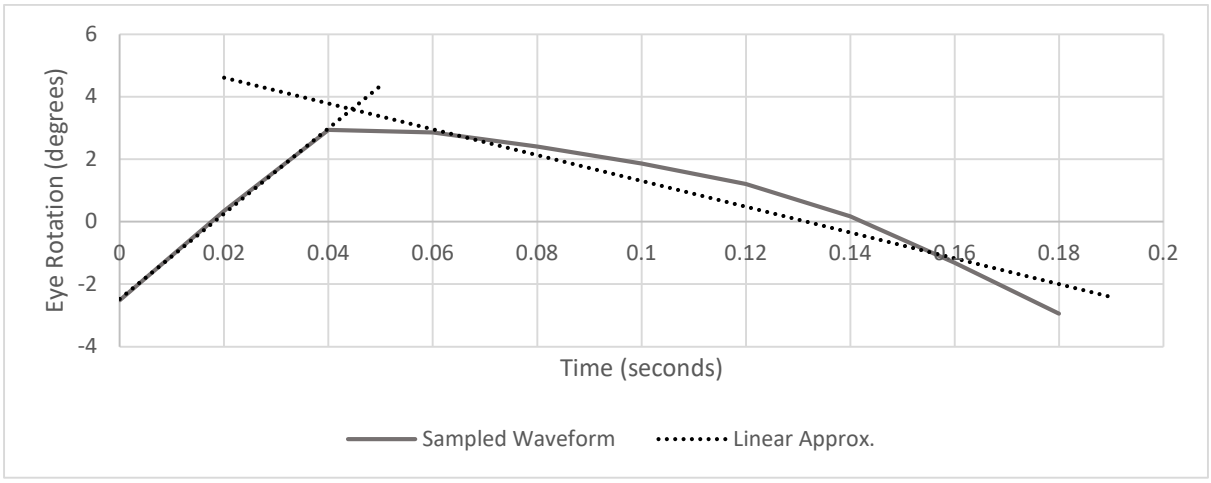
a. A complete wavelength (incorporating both fast and slow phases) was selected from the eye tracking data (dotted black line in Figure 1a). The original waveform was sampled every 0.02 seconds (solid line in Figures 1a and 1b) to be consistent with the frame-rate of the smartphone app. [9]
b. Independent linear approximations of the fast and slow phases were made using least squares linear regression best-fit lines (shown in Figure 1b).
c. The amplitude and frequency of the linear approximated waveform were systematically adjusted to create a series of parametric waveforms, a sample of which are shown in Figure 1c. The original linearly approximated waveform had amplitude and frequency of approximately 5.4° and 5 Hz respectively. A realistic range of

amplitudes and frequencies were generated with five different amplitudes of 1°, 3°, 5°, 8° and 11° at three different frequencies: 1.25 Hz, 2.5 Hz and 5 Hz.

(a)



(b)



(c)

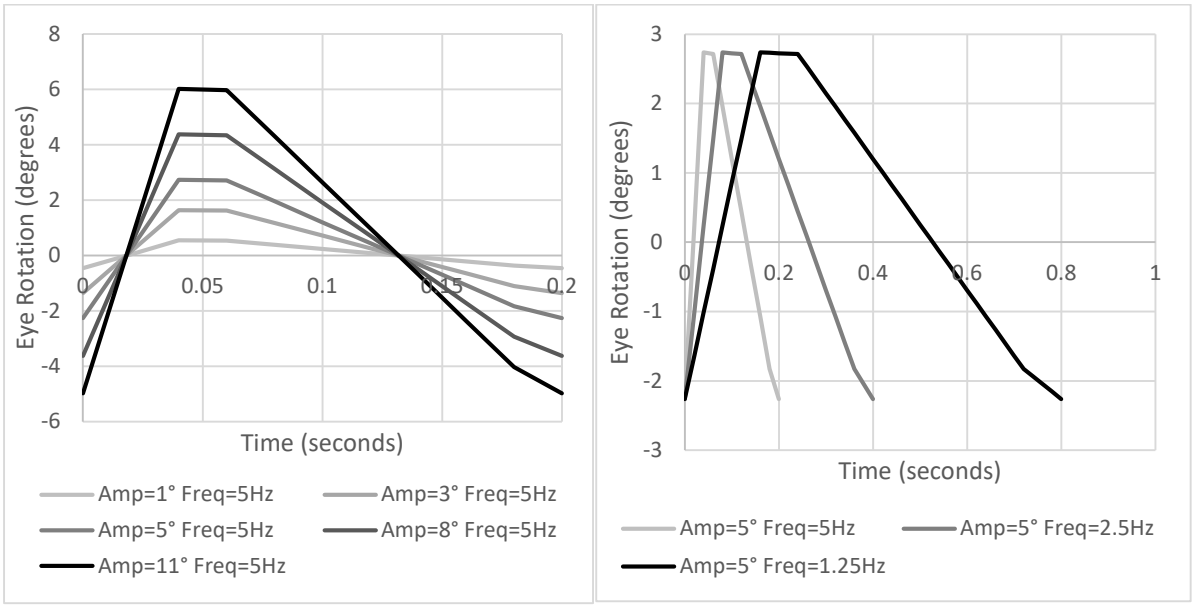


Figure 1: Procedure for artificial horizontal right-beat nystagmus waveform generation to simulate different severities of oscillopsia. (a) the original waveform from EyeLink 1000 Plus (dotted line) and the sampled waveform every 0.02 s (solid line). (b) the sampled waveform from (a) and its linear

approximation. (c) examples of the resulting artificial waveforms varying in amplitude (left) and frequency (right).

The Unity game engine was used to develop the VR smartphone app. An interactive menu, inside the virtual environment, permitted the selection of the different nystagmus simulations as well as the option of selecting no simulation (stationary). Once an option was selected, the user found himself/herself in a virtual room facing an ETDRS logMAR chart with the selected oscillopsia simulation beginning automatically. [10] The logMAR chart was placed 4 m away from the observer in the virtual environment. Its size was optimised via a preliminary test involving three participants to ensure that a VA of at least 0.2 logMAR could be achieved. The optimised virtual logMAR chart was three-times larger than in real life due to the resolution limit of the smartphone display.

A smartphone-VR arrangement was used which tracks head rotation and updates the display accordingly but not eye movement. The simulation was run on a Samsung Galaxy S7 smartphone placed inside a Homido V2 headset. The Samsung Galaxy S7 offered one of the best pixel densities (577 pixels/inch) and most powerful processors to ensure smooth replication of the computationally demanding VR oscillopsia simulation. The Homido V2 headset was chosen for its clear optics and customisation of focus (lens-to-display distance) and inter-pupillary distance so the sharpness of the display could be optimised for each participant.

Data Collection

Fifty adult participants with no known ocular conditions were recruited onto a prospective study with ethical approval (University of Sheffield, 120252598). All participants gave written consent and were screened according to the inclusion criteria (no history of strabismus,

nystagmus or oscillopsia, aged 18-30 and a VA of 0.20 logMAR or better using a physical 3m chart with both eyes open and refractive correction if required). Participants were asked to don the Homido V2 headset with the inserted smartphone. Refractive correction eyewear could be worn in conjunction with the VR headset and was permitted throughout the study. Before acquisition of results, participants were encouraged to optimise the focus of the headset while observing the virtual logMAR chart under stationary conditions.

Participants first viewed a logMAR chart in VR without oscillopsia and then subsequently for each of the 15 oscillopsia simulations. To avoid the participant memorising the virtual logMAR chart, eight variations of the chart were produced and randomly allocated to the different simulations. The 15 oscillopsia simulations were presented to the participants in a random order with both participant and examiner blinded to which simulation was initiated. A logMAR score was recorded for each oscillopsia simulation using letter-by-letter scoring and line-based termination when two or more letters on a line were incorrectly identified. [11] The time taken to read the vision chart and provide a result was measured in 27 of the participants. Typically, the total examination time was 25 minutes.

Data Analysis

In this analysis we have used the parameter of "intensity" to describe the severity of each simulation. The intensity of a nystagmus waveform is defined as the frequency x amplitude and is mathematically equivalent to the average velocity of the waveform.

For each oscillopsia simulation, the change in VA was determined by subtracting the result of the "stationary" VA (recorded in VR), from the VA recorded for each simulation to allow for differing baseline VAs between participants. It is also the case that whilst the absolute VA

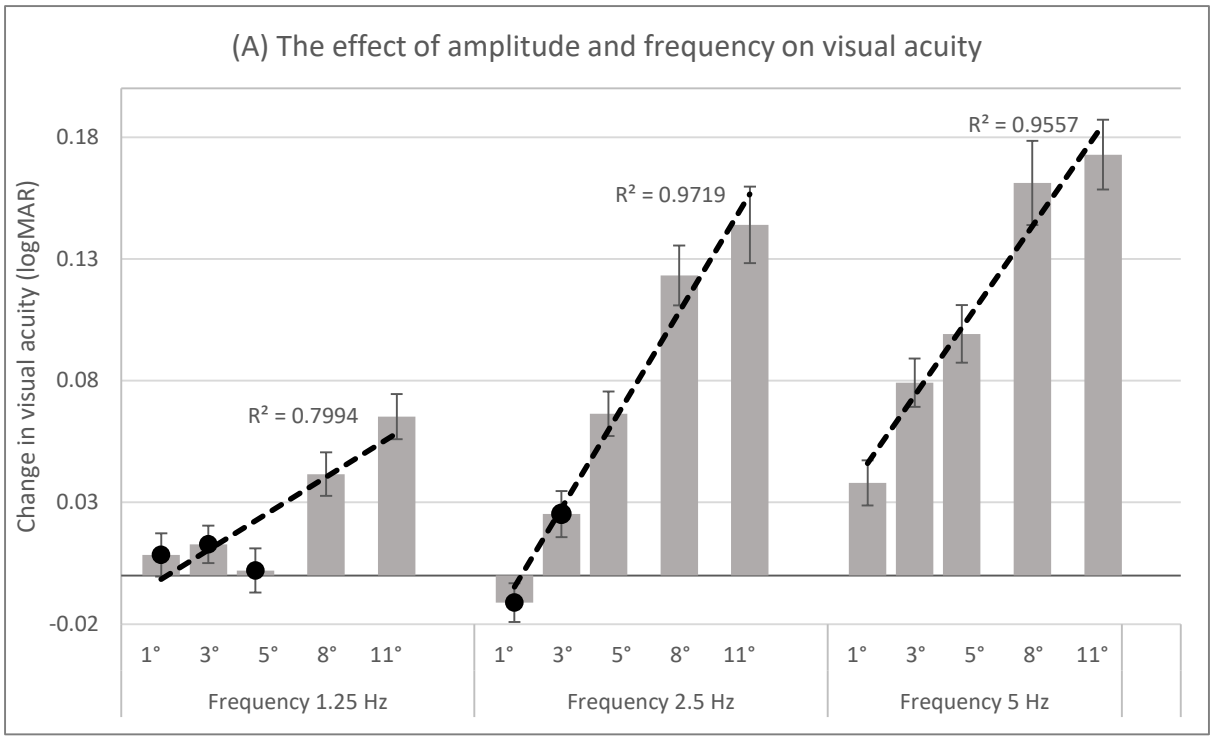
logMAR scores recorded in VR are not comparable to a real-world chart (due to the chart being 3x larger in VR), the **relative change** in logMAR is mathematically independent of chart size. So the recorded values on the larger chart in this study are mathematically comparable to changes in logMAR that would be recorded on regular sized charts.

One-tailed paired t-tests were performed, with a Bonferoni correction of α, to compare the VA measured under stationary conditions to each of the oscillopsia simulations to confirm statistically significant worsening of VA with simulated oscillopsia ($\alpha = 0.0033$). These results were supported by a Cohen's d effect size test. A Spearman's Rank correlation coefficient was calculated to indicate consistency in VA decline as intensity of the oscillopsia simulation increased.

Results

VA response to simulated oscillopsia

The mean change in VA across all 50 participants for each frequency/amplitude combination is presented in Figure 2A (a larger value indicating worse VA). The intensity of the simulation (amplitude x frequency) [12] is plotted against change in VA in Figure 2B with a potentially linear relationship plotted for the first 11 results in light grey.



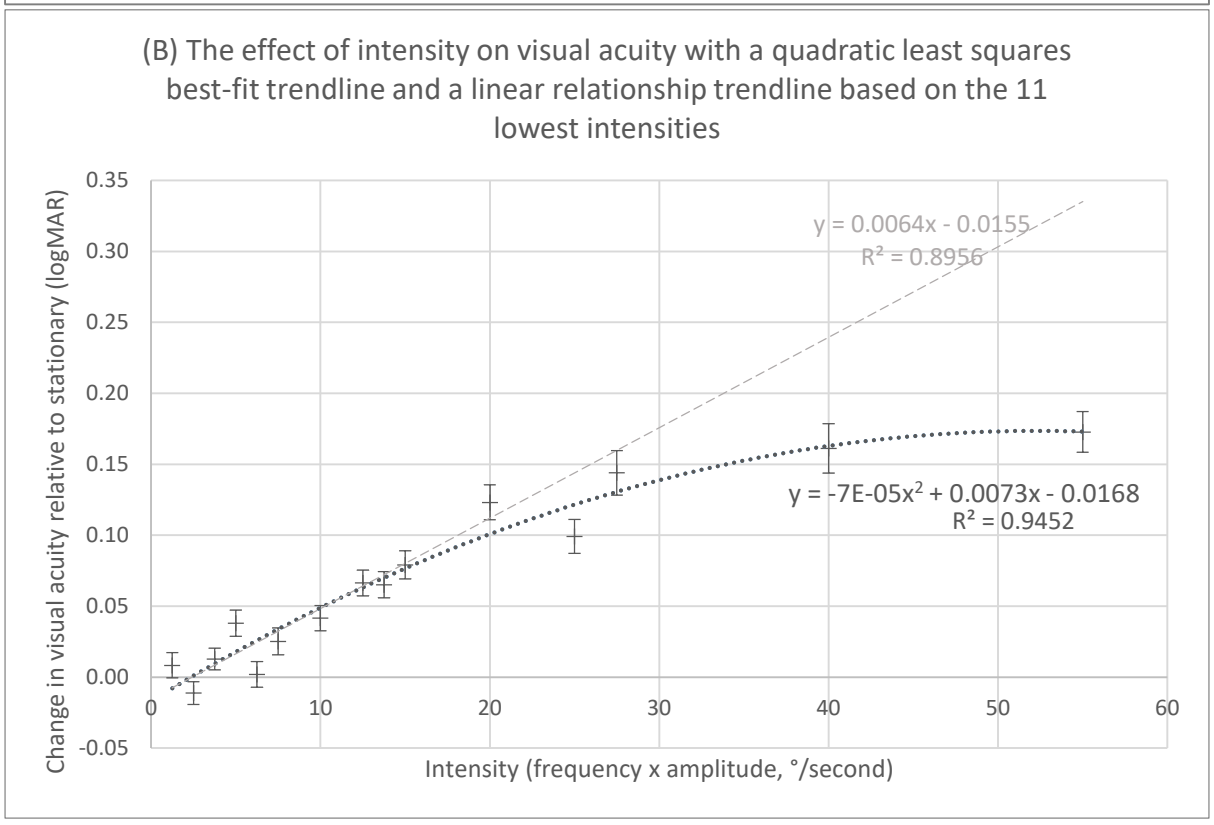


Figure 2(A): Change in visual acuity with amplitude and frequency. Linear regression best-fit lines have been plotted for each frequency grouping. Error bars represent the standard error in each of the mean value recordings. The five black points mark a lack of significant reduction in VA compared to stationary VA.

Figure 2(B): Simulation intensity (frequency x *amplitude) against change in visual acuity relative to stationary, with a quadratic best-fit trend line (dotted line). A linear relationship (light grey line) is plotted for the 11 lowest intensity results (i.e. before the quadratic best-fit curve beings to level off). Error bars show standard error in the means.*

Figure 2A shows that VA worsens with increasing frequency and amplitude of the oscillopsia simulation. Each incremental increase in amplitude or frequency resulted in worse VA with the exception of two points: frequency 1.25 Hz, amplitude 5° and frequency 2.5 Hz, amplitude 1°. However, a one-tailed paired t-test that compared VA for each simulation to VA under stationary conditions (in VR) revealed five of the least severe simulations did not produce a significant reduction in VA ($p > 0.0033$) – indicated by the five black points in Figure 2A. These five points had a Cohen's d score of 0.05 - 0.61 while the remainder of simulations achieved >0.8 (largest = 1.34 for the 11°, 5 Hz simulation), supporting the t-test results and confirming significance of VA reduction in all simulations above an intensity of 7.5 °/s. The observed improvement in VA relative to baseline at 1°, 2.5 Hz was 0.01 logMAR, which is not statistically or clinically significant. The biggest average reduction in VA was 0.17±0.1 logMAR occurring at 5 Hz with 11° amplitude. Figure 2A displays a linear fit to relate a decrease in VA with increasing amplitude as the frequency has been fixed within each group. The linear fit model loosely agrees with the trend but begins to deviate at higher intensity combinations of amplitude and frequency.

Figure 2B indicates that the relationship between VA and intensity is approximately quadratic. The Spearman's rank correlation coefficient for these data is 0.96 indicating a strong relationship, despite greater variability at lower intensities. A linear fit correlates well at the lower intensities (light grey dashed line) but deviates as the intensity increases beyond 20 °/s as the observed relationship begins to level off.

The data allows for analysis of each incremental change in amplitude while maintaining the same frequency and vice-versa to calculate change in VA per unit of intensity (or velocity, °/s).

This allows us to directly compare like-for-like increases in amplitude or frequency to determine which has a greater effect on VA. Incremental increases in amplitude produced an overall average reduction in VA of 0.0043 logMAR per unit of intensity; whereas incremental increases in frequency produced a similar reduction of 0.0044 logMAR per unit of intensity.

Time taken to read vision chart

The time taken to read the vision chart was measured in 27 participants. Figure 3 shows the correlation between increased intensity of the simulation and time taken by participants to examine the chart before producing a result.

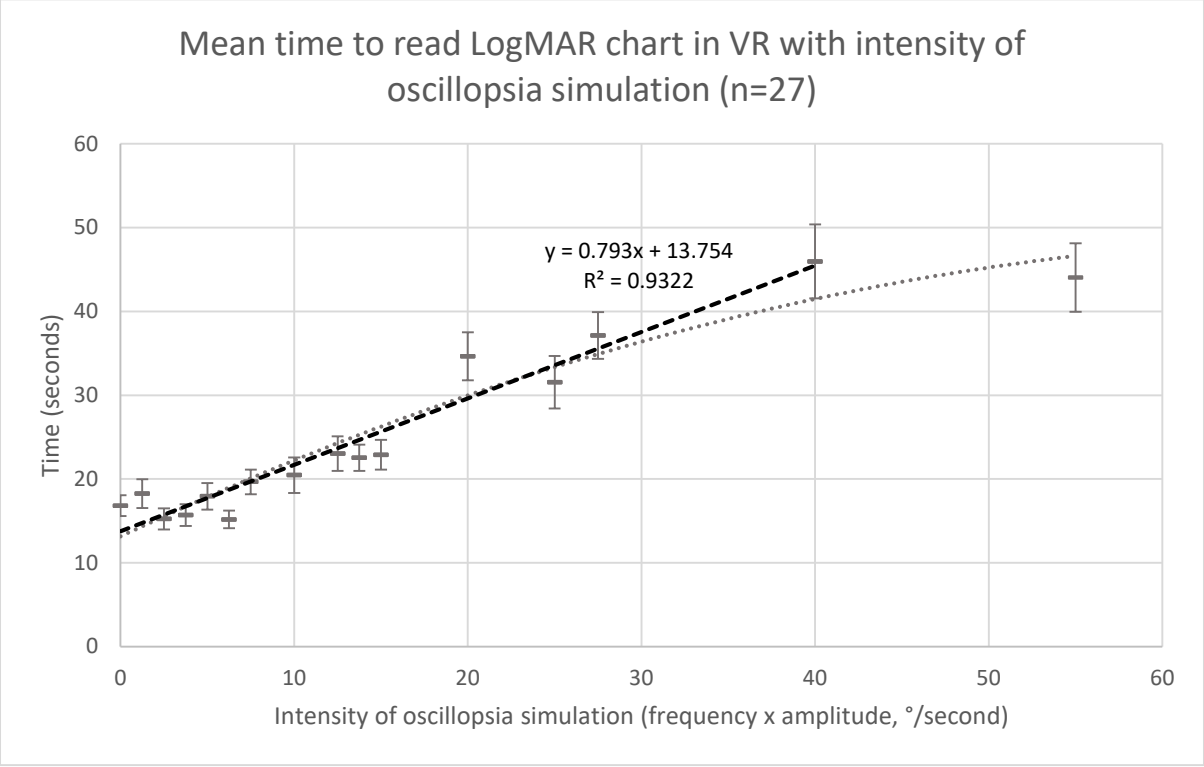


Figure 3: Mean time taken to read the LogMAR chart in VR with intensity of the oscillopsia simulation. The data were collected for 27 of the participants. The dashed linear best-fit line is plotted excluding the last point for the highest intensity simulation.

Figure 3 shows an increase in time taken to view the chart with increasing intensity, ranging from 15 to 46 seconds over the intensities tested. The error bars in Figure 3 correspond to the

standard error in the mean for each simulation. The linear relationship shown is plotted when omitting the result for the highest intensity simulation.

Discussion

There is limited literature relating VA to acquired nystagmus with oscillopsia. [13, 14] Bandini et al (2001) compared VA before and after medication in acquired nystagmus patients, but the relationship between amplitude, frequency and VA was not explored. [14] There have been numerous studies into the effects of velocity on dynamic VA and those related to infantile nystagmus, which, although relevant, are not directly aimed at or related to the visual effects of oscillopsia. [3, 15, 16] There have been several studies investigating VA response to image motion and while the methodology varies most involve movement of a target on a flat screen/projector possibly with the addition of magnifying eyewear. These tests evaluate dynamic VA in the presence of head motion and eye movement with a variety of different targets and VA tests. While this may be adequate for the purposes in their studies, our study takes a different approach which is arguably more closely aligned to the effects of oscillopsia – by adapting our previously reported VR simulation of oscillopsia. [9] The advantage of performing this experiment in VR, as opposed to a flat screen or physical movement/moving object, is immersion and the experience of the whole environment moving, as would be the case for patients with oscillopsia, creating a more realistic simulation of the condition. This isolates the effects of oscillopsia from realistic nystagmus waveforms without interference of saccadic eye movements, head movement or any compensatory eye/head movements. Despite the immersive nature of the simulation, no participants reported any nausea.

This study has confirmed that as the amplitude and/or frequency of the simulated oscillopsia are increased, VA worsens. Figure 2B and the Spearman's coefficient of 0.96 indicate that an

increase in the intensity of the oscillopsia simulation strongly correlates with a worsening of VA. This relationship can be explained by retinal slip – increasing the amplitude and frequency of oscillopsia increases the movement speed of the image on the retina. [17] The smearing of the point spread function (PSF), and an inability to form a stable image on the fovea, leads to poorer VA. The subsequent formulation of a simple theoretical understanding linking oscillopsia severity to physical blurring component of VA reduction provides justification for this explanation and offers deeper insight for interpretation of the observed results.

If considering VA reduction (ΔVA) entirely as a result of physical blurring of the image on the retina, then:

$$\Delta VA \quad \propto \quad \Delta PSF_{\overline{w}}$$

$$PSF_{\overline{w}} = \overline{v} * t_{acq}$$

Where $PSF_{\overline{w}}$ refers to the average width of the point spread function and corresponds to the magnitude of blurring of the image on the retina; $\overline{v}$ is the average velocity of eye movement in °/s, t_{acq} is the image acquisition time. In this case t_{acq} may be a complex combination of the physiological processes related to image acquisition/processing by the brain and refresh rate of the display. Under the assumption that the acquisition time, t_{acq}, is mostly constant, the width of the PSF is proportional to velocity with t_{acq} the proportionality constant of the relationship.

$$\Delta VA \propto \overline{v} \; (or \; intensity)$$

$$\therefore \Delta VA \propto f * A$$

Therefore, the theory predicts a linear increase in the PSF (i.e. linear reduction in VA) with the multiplication of frequency, *f*, and amplitude, *A*. This theoretical description of VA decline with increasing intensity of retinal image movement is offered to place the results within a framework of understanding of the physical blurring component contributing to loss of VA.

Relationship between VA, frequency and amplitude

Figure 2A allows the effects of frequency and amplitude to be observed independently and reveals a strong trend in VA reduction when either frequency or amplitude are increased. Two results disagree with this trend: Amplitude = 1°, Frequency = 2.5 Hz and Amplitude = 5°, Frequency = 1.25 Hz but these small changes in VA were statistically insignificant. There is an uncertainty associated with each reading of the logMAR chart and a smaller change in VA for relatively mild oscillopsia makes the percentage error in these results greater, potentially contributing to their lack of significance.

The prediction of a linear relationship between intensity and VA reduction provides a good fit ($R^2 = 0.896$) at lower intensities but deviates beyond an intensity of approximately 20 °/s, as shown in Figure 2B by the linear fit to the first 11 intensities of the observed results. The greater uncertainty at very low intensities reduces the R^2 correlation coefficient and hampers detailed assessment regarding the true relationship in this region. A possible practical difference not accounted for in the predictive model might be the human visual system's ability to tolerate low velocity retinal image movement resulting in a lesser impact on VA, as reported in previous studies. [15, 18, 19]

The notable difference between the prediction and the observed data is the gradual levelling-off of worsening VA at greater intensities, conflicting with the predicted continuous linear worsening of VA. This infers that the levelling off of VA reduction in the observed results is

not accounted for by physical blurring alone This discrepancy is likely related to either the experimental methodology or a human compensation that mitigates the effects of physical blurring. The literature in a related field of dynamic VA supports worsening VA with increasing velocity rather than the levelling off observed in this study, which may infer that the experimental procedure could be to blame. [15, 18] Participants in our study were not given a set time period to view the charts and, on average, took longer to read the charts at higher intensities (e.g. 15 seconds at an intensity of 2.5 to 46 seconds at an intensity of 40). This will have a competing effect on the trend of worsening VA as intensity increases and is likely to contribute to the levelling-off observed. Another potential factor is the possibility that the Samsung Galaxy S7 smartphone was unable to run at >50 frames per second due to insufficient graphical processing capabilities. In this scenario it would be unable to accurately recreate the eye movement waveforms, however, a benchmark test concluded the phone produced a frame rate in excess of 50 frames per second at all times over a 30-minute testing period (data acquired using the GameBench Android App). Alternatively, the 50 frames per second itself could be the cause, as this results in the VR eye movements following discrete movement steps every 20 ms. At lower intensities this is likely to have less of an effect but at higher velocities the dwell time provided by these short stationary periods are likely to have a greater relative impact. This would result in a smaller than expected reduction in VA at higher intensities. This effect is potentially exacerbated by the flattening of the waveform at its peak, as a result of the linear idealisation of the waveforms, and may create a dwell time for the participant. Although preliminary tests confirmed that there was no perceptible foveation period or noticeable period of no motion in any of the simulations. The effect of discretisation of the waveform could be investigated further by varying the frame rate and observing the change in shape of the curve in Figure 2B but this was beyond the scope of this study. Possible frame rate effects of digital systems should be considered by others attempting similar studies.

The prediction indicates that frequency and amplitude of oscillopsia should affect VA equally (as both are proportional to velocity). This has been observed through the calculation of similar quantities for worsening VA per unit of intensity for independent changes in amplitude and frequency, and witnessed in the approximate linear trends in Figure 2A as amplitude is increased. However, the linear effect of frequency should be reflected by an increasing gradient of the lines as frequency is increased. This is not observed when moving from 2.5 Hz to 5 Hz, but this is likely the result of the levelling off at high intensities (artificially reducing the gradient) as discussed above. The insignificant -0.01 logMAR improvement in VA (i.e. negative change in logMAR) at 1°, 2.5 Hz also exacerbates the gradient for the 2.5 Hz dataset.

Time to See

Time to see has been shown been shown to be an important consideration in congenital nystagmus [20] but also applies to those who experience oscillopsia. Figure 3 clearly indicates that participants took longer to examine the chart as the severity of simulated oscillopsia was increased. The exact nature of the relationship is roughly linear or possibly a shallow quadratic. The levelling off of the curve is most likely a factor of two things: 46 seconds is probably approaching the limit of time that participants thought was acceptable before providing an answer and the intensity of the highest intensity simulation (55 °/s) may have been unpleasant causing participants to spend less time than was required to give an optimal response. With the omission of the highest intensity simulation on Figure 3 the graph displays a linear relationship with a correlation coefficient of $R^2 = 0.93$. The linear relationship suggests for every degree per second increase in velocity of virtual eye movement the time taken to observe the chart increased by approximately 0.8 seconds. How this relationship for time to read the chart in this study relates to time to see for oscillopsia sufferers in everyday life is unclear but may provide

a loose indication. It should be noted that while participants were encouraged to provide an answer they were not informed that the test was being timed.

Limitations

The eye movement waveforms used to simulate oscillopsia were approximations based on a real nystagmus waveform. The approximation process has resulted in idealisation, such as the flattening of the peak due to the sampling of the waveform and the non-conformity in the linear estimation in the slow phase (Figure 1b). These are only minor discrepancies relative to the actual waveform but it is prudent to be aware of this source of uncertainty when relating these results to real oscillopsia sufferers.

The relationship investigated relates to only a single type of nystagmus: horizontal right beat jerk nystagmus. Whether the relationship described has similar characteristics for other forms of nystagmus cannot be concluded from this study. Horizontal jerk nystagmus was chosen for this experiment due to readily available data and as it is seen in both acquired and infantile nystagmus. [27, 28] The number of different simulations was a compromise between time required of each participant (approximately 25mins) and quantity of data. Incorporating more simulations may have resulted in poorer participant concentration and compliance, degrading the quality of the results.

The chosen frequencies and amplitudes cover a sufficient range to determine a relationship between reduction in VA and nystagmus intensity and was mostly reflective of typical velocities of nystagmus eye movements. However, there is a lack of physiological accuracy in the waveform's constitution in the velocity of the fast phase for the lower frequency waveforms (1.25 Hz simulations). The fast-phase in the horizontal jerk nystagmus waveform is a saccade

and the fast phase velocities of 6 °/s to 69 °/s simulated at 1.25 Hz are too slow for saccadic eye movement. Despite this inaccuracy, simulations at lower frequencies were necessary to provide completeness to the relationship at low image motions. A second subtler source of inaccuracy in the fast phase is the potential for different physiological responses when imposing oscillopsia externally, as in this study, compared to the response of a real patient with oscillopsia. A real patient would experience a degree of saccadic suppression during a self-generated fast phase, which is unlikely to happen in the volunteers experiencing a simulated waveform in VR. [29] This could lead to an overestimate in the severity of VA reduction.

Despite the Samsung Galaxy S7 offering one of the best pixel densities, the limits of resolution of the phone/headset combination meant the size of the chart was increased to allow scope for meaningful changes in VA (i.e. if the best achievable VA was 0.4 logMAR – due to the resolution limit – there is little capacity to measure a reduction in VA due to the oscillopsia simulations). The maximum observed reduction in VA of 0.17 logMAR should be unaffected by this, as changes in VA are not affected by the size of the chart.

Clinical Significance

Through simulation, this study has provided evidence that oscillopsia and greater intensity nystagmus waveforms are likely to cause greater worsening of VA (excluding co-existing pathologies). The relationships identified in this paper contribute to our knowledge of the effects of oscillopsia on VA but, due to the number of assumptions made and limitations of the study, cannot be used directly in clinic to relate an individual's nystagmus waveform to an anticipated reduction in VA.

The observed maximum mean reduction in VA of 0.17 logMAR equates to approximately two lines (or 9 letters) on the ETDRS logMAR chart, which may be considered less than expected for the intensities of oscillopsia simulated. This is partly due to the experimental factors already discussed (unlimited time allowed to view the logMAR charts in VR and smartphone frame rate) but it could also be attributed to observing the effect of oscillopsia in otherwise normally developed visual systems and the absence of any other conditions typically observed in association with nystagmus. This theory is supported by Dunn et al. who concluded that eye movements themselves may not significantly degrade VA in adults with infantile nystagmus. [21] It has been previously suggested that the severity of the oscillopsia may also decrease over time. [29, 22] Ophthalmoplegia patients with oscillopsia have been found to have raised binocular motion detection thresholds, indicative of a mechanism that adapts to excessive retinal slip and hence, reduces the severity of oscillopsia. [23] This experiment is most comparable to those who have not adapted to their oscillopsia. The authors acknowledge that patients who experience oscillopsia may have concurrent pathology and/or vision defects. This study does not take other pathology into account but attempts to isolate and assess the impact of oscillopsia alone. Here it is assumed that no previous vision defects or concurrent pathology exists and that this experiment offers a representative experience of oscillopsia, as implied by the patient feedback from our previous oscillopsia app. [9] There is also an argument that over time, acquired nystagmus sufferers may adapt and exhibit a higher tolerance to retinal slip, lessening the impact of oscillopsia on VA. [22, 23, 24] Recordings of head and eye movements have shown that the magnitude of retinal slip is often larger than the reported oscillopsia (Leigh et al., 1994). [22] Questionnaires that evaluate patients' subjective complaint of oscillopsia have revealed that a higher tolerance is associated with personal attitude and the perception of the amount of control over the disease. [24, 30] Therefore, it is important to consider that the simulated oscillopsia does not represent all aspects of living with nystagmus/oscillopsia and,

hence, the effect on VA may not be as expected. It is acknowledged that the reduction in VA is only one component of oscillopsia and does not communicate the complete impact of the condition. [25, 31] For example, the increased time taken to observe the charts at higher intensities supports that increased "time-to-see" is also a factor when living with oscillopsia. [26] The increased time to observe the chart with severity of oscillopsia may impact on vision testing procedure for oscillopsia patients and time allocated for vision tests in clinic.

Additionally, the prediction that amplitude and frequency have an equal effect on VA for oscillopsia sufferers is confirmed by the observed data; adding to clinical understanding and potentially influencing patient management.

Conclusion

Assessing the direct impact of oscillopsia on VA is difficult due to associated conditions that may affect vision in patients with acquired nystagmus patients and the lack of baseline VA for comparison. Consequently, the literature is sparse. VR offers a unique opportunity to approximate the isolated impact of oscillopsia on individuals without any associated ocular problems. This study presents a novel method of investigating the effects of oscillopsia on VA by simulating oscillopsia with a horizontal jerk nystagmus at varying amplitudes and frequencies. Participants demonstrated a worsening of VA as the amplitude and/or frequency of the waveform were increased. They also took increased time to examine the chart increased, with every degree/second increase in average velocity resulting in a 0.8s addition in examination time. The amplitude and frequency were found to worsen VA equally, as predicted by theoretical understanding. Discrepancies between a predictive model and observations revealed possible limitations of the method as 20 ms frames offered potential for increased dwell-time which was compounded by longer chart viewing times at higher intensities, but this

itself has offered interesting insights. These results not only consolidate the assumption that VA degrades with oscillopsia but also provide quantitative evidence.

References

[1] Abadi RV, Bjerre A. Motor and sensory characteristics of infantile nystagmus. Br J Ophthalmol. 2002;86(10):1152-1160.

[2] Felius J, Fu VL, Birch EE, Hertle RW, Jost RM, Subramanian V. Quantifying nystagmus in infants and young children: relation between foveation and visual acuity deficit. Invest Ophthalmol Vis Sci. 2011;52(12):8724-8731.

[3] Weiss AH, Kelly JP, Phillips JO. Relationship of slow-phase velocity to visual acuity in infantile nystagmus associated with albinism. J AAPOS. 2011;15(1):33-39.

[4] Felius J, Muhanna ZA. Visual deprivation and foveation characteristics both underlie visual acuity deficits in idiopathic infantile nystagmus. Invest Ophthalmol Vis Sci. 2013;54(5):3520-3525.

[5] Hanson KS, Bedell HE, White JM, Ukwade MT. Distance and near visual acuity in infantile nystagmus. Optometry Vision Sci. 2006;83(11):823-829.

[6] Dickinson CM, Abadi RV. The Influence of Nystagmoid Oscillation on Contrast Sensitivity in Normal Observers. Vision Res. 1985;25(8):1089-1096.

[7] Chung STL, LaFrance MW, Bedell HE. Influence of Motion Smear on Visual Acuity in Simulated Infantile Nystagmus. Optometry Vision Sci. 2011;88(2):200-207.

[8] Currie DC, Bedell H, Song S. Visual acuity for optotypes with image motions simulating congenital nystagmus. Clin Vis Sci, 1993;8(1):73-84.

[9] Randall D, Griffiths H, Arblaster G, Bjerre A, Fenner F. Simulation of oscillopsia in virtual reality. Br Ir Orthopt J. 2018;14(1):45-49.

[10] National Eye Institute. Early treatment diabetic retinopathy study (ETDRS): manual of operations. Springfield (VA): US Dept of Commerce, National Technical Information Service; 1985.

[11] Carkeet A. Modeling logMAR visual acuity scores: effects of termination rules and alternative forced-choice options. Optometry Vision Sci. 2001;78(7):529-38.

[12] Glaser JS. Neuro-Ophthalmology. 3rd ed. Philadelphia (PA): Lippincott Williams & Wilkins; 1999.

[13] Guinand N, Pijnenburg M, Janssen M, Kingma H. Visual acuity while walking and oscillopsia severity in healthy subjects and patients with unilateral and bilateral vestibular function loss. Arch Otolaryngol Head Neck Surg. 2012;138(3):301-306.

[14] Bandini F, Castello E, Mazzella L, Mandcardi GL, Solaro C. Gabapentin but not vigabatrin is eVective in the treatment of acquired nystagmus in multiple sclerosis: how valid is the GABAergic hypothesis?. J Neurol Neurosurg Psychiatry. 2001;71:107-110.

[15] Demer JL, Amjadi F. Dynamic Visual Acuity of Normal Subjects During Vertical Optotype and Head Motion. Invest Ophthalmol Vis Sci. 1993;34(6):1894-1906.

[16] Kohmura Y, Aoki K, Honda K, Yoshigi H, Sakuraba K. The relationship between dynamic visual acuity and saccadic eye movement. Hum Perform. 2008;5:23-30.

[17] Binder MD, Hirokawa N, Windhorst U. Encyclopedia of Neuroscience. 2009 ed. Berlin (Germany): Springer. 2009.

[18] Barnes GR, Smith R. The effects of visual discrimination of image movement across the stationary retina. Aviat Space Envir Md. 1981;52(8):466-472.

[19] Westheimer G, McKee SP. Visual acuity in the presence of retinal-image motion. J Opt Soc Am. 1975;65(7):847-850.

[20] Jones PH, Harris CM, Woodhouse M, Margrain TH, Ennis FA, Erichsen JT. Stress and Visual Function in Infantile Nystagmus Syndrome. Invest Ophthalmol Vis Sci. 2013;54(13):7943-7951.

[21] Stahl JS, Averbuch-Heller L, Leigh J. Acquired Nystagmus. Arch Ophthalmol. 2000;118(4):544-549.

[22] Jacobs JB, Dell'Osso LF. Congenital nystagmus: Hypotheses for its genesis and complex waveforms within a behavioral ocular motor system model. J Vision. 2004;4(7):604-625.

[23] Diamond MR, Ross J, Morrone MC. Extraretinal Control of Saccadic Suppression. J Neurosci. 2000;20(9):3449-3455.

[24] Dunn MJ, Margrain TH, Woodhouse M, Ennis FA, Harris CM, Erichsen JT. Grating Visual Acuity in Infantile Nystagmus in the Absence of Image Motion. Invest Ophthalmol Vis Sci. 2014;55(4):2682-2686.

[25] Bronstein AM, Hood JD. Oscillopsia of peripheral vestibular origin. Central and cervical compensatory mechanisms. Acta Otolaryngol. 1987;104(3-4):307-314.

[26] Wist ER, Brandt T, Krafczyk S. Oscillopsia and Retinal Slip: Evidence Supporting a Clinical Test. Brain, 1983;106(1):153-168.

[27] Acheson JF, Cassidy L, Grunfeld EA, Shallo-Hoffman JA, Bronstein AM. Elevated visual motion detection thresholds in adults with acquired ophthalmoplegia. Br J Ophthalmol. 2001;85(12):1447-1449.

[28] Grunfield EA, Morland AB, Bronstein AM, Gresty MA. Adaptation to oscillopsia: a psychophysical and questionnaire investigation. Brain. 2000;123(2):277-290.

[29] Herdman SJ, Hall CD, Schubert MC, Das VE, Tusa RJ. Recovery of dynamic visual acuity in bilateral vestibular hypofunction. Arch Otolaryngol Head Neck Surg. 2007;133(4):383-389.

[30] McLean RJ, Windridge KC, Gottlob I. Living with nystagmus: a qualitative study. Br J Ophthalmol. 2012;96(7):981-986.

[31] Anson ER, Gimmon Y, Kiemel T, Jeka JJ, Carey JP. A Tool to Quantify the Functional Impact of Oscillopsia. Front Neurol. 2018;9(142).

[32] Erichsen JT, Woodhouse JM, Margrain TH, Ennis F, Harris CM, Jones PH. The effects of stress on nystagmus (INS): acuity vs. time to see. Acta Ophthalmol. 2010;88(s246).