Title: Investigating Head Movements Induced by "Riloid" Patterns in Migraine and Control Groups using a Virtual Reality Display

Short title: Head Movements Induced by "Riloid" Patterns

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Summary

Certain striped patterns can induce illusory motion, such as those used in op-art. The visual system and the vestibular system work together closely, and so it is possible that illusory motion from a visual stimulus can result in uncertainty in the vestibular system. This increased uncertainty may be measureable in terms of the magnitude of head movements. Head movements were measured using a head-mounted visual display. Results showed that stimuli associated with illusory motion also seems to induce greater head movements when compared to similar stimuli. Individuals with migraine are more susceptible to visual discomfort, and this includes illusory motion from striped stimuli. However, there was no evidence of increased effect of illusory motion on those with migraine compared to those without, suggesting that while motion illusions may affect discomfort judgements, this is not limited to only those with migraine.

Key words

Op-art; visual discomfort; virtual reality; motion illusions, migraine

Introduction

Visual discomfort is a broad term encompassing a variety of symptoms including headache, eyestrain and illusory motion, often described as shimmer (Sheedy et al., 2003). Op-art-based visual stimuli, typically those including high contrast gratings, can cause visual discomfort, particularly illusions of motion (Troncoso et al., 2008; Patzwahl and Zanker, 2000; Zanker et al., 2003; Zanker et al., 2004; Zanker et al., 2010). Op-art based stimuli known as "riloid" stimuli (see Figure 1) have previously been demonstrated to cause illusions of motion in observers in a systematic way (Zanker et al., 2003; Zanker et al., 2004; Zanker et al., 2010), by varying the spatial frequency, or the waviness of the lines. In particular, the spatial frequency of riloid patterns has been shown to affect electrophysiological (VEP) responses in the early visual areas of the brain (O'Hare et al., 2015; O'Hare, 2017a; O'Hare, 2017b).

Visual information provides an important signal for the vestibular response (for a review, see Wade and Jones, 1997). There are many studies showing that visual information from stable environments can stabilise posture, whereas moving visual information can decrease postural stability (for a review see Redfern et al., 2001). Cells in the vestibular nuclei receive input from the labyrinthine system. Those cells of the vestibular nuclei associated with gaze stability respond to optokinetic stimuli, but not those cells associated with head movements, suggesting integration of vestibular and visual information relevant to posture does not occur in the vestibular nuclei (for a discussion, see Cullen, 2012). However, cells in the higher visual areas such as the medial superior temporal area (MSTd) and the ventral intraparietal areas (VIP) are thought to integrate visual and vestibular information relevant to posture, as these are visual areas that also respond to physical motion in the absence of light stimulation (see DeAngelis and Angelaki, 2012 for a discussion). Further, cells in MSTd combine the information from visual and vestibular sources optimally, according to Bayesian models (Angelaki et al., 2011). Additionally, chemical deactivation of MSTd (using microinjections of GABA) impaired the ability to discriminate heading direction based on visual, vestibular and combined cues, showing strong evidence that this area is involved in the integration of visual and vestibular cues relevant to self-motion (Gu et al., 2012).

Certain stimuli can evoke perceptions of motion, for example illusions such as the "peripheral drift illusion" (Kitaoka and Ashida, 2003). Perceptions of motion can also occur from the motion after-effect (Mather et al., 1998). Illusory motion perception from the "Rotating Snakes" illusion is also associated with medial temporal areas (Kuriki et al., 2008; Ashida et al., 2012). Importantly, it has been shown that illusory motion from the motion after-effect, can increase postural sway (Holten et al., 2014). Conversely, individuals with reduced postural stability tend to be more likely to perceive illusory self-motion (vection) when exposed to moving visual patterns, specifically optic flow stimuli (Apthorp et al., 2014). Uncomfortable visual stimuli might increase uncertainty, in which case increased movement of the observer is predicted when the stimuli are uncomfortable to look at.

***************************figure 1 here********************

Migraine and Visual Response

Migraine is a common neurological disorder (Lipton et al., 2001). The Headache Classification Subcommittee of the International Headache Society (2013) require five or more headache attacks accompanied by either nausea/vomiting, or photo/phonophobia, to warrant a diagnosis. The attacks must last 4-72 hours when left untreated, and involve two or more of the following criteria: pulsing headache, lateralised to one side, aggravated by physical activity, moderate to severe pain.

Migraine sufferers show sensory differences compared to controls, particularly in visual processing. One of the sub-classifications of migraine is migraine-with-aura (MA), which is defined as those experiencing sensory disturbances immediately preceding the onset of the headache itself (IHS, 2013). Those who do not experience these sensory disturbances preceding the attack are classified as migraine without aura (MO). Individuals with migraine also show differences in sensory processing in between attacks (for a review see O'Hare and Hibbard, 2016). In particular, sufferers typically show poorer performance on tasks involving motion processing (Antal et al., 2005; McKendrick et al., 2006; Ditchfield et al., 2006; Shepherd et al., 2012; Braunitzer et al., 2012; Tibber et al., 2014). Additionally, those with MA have shown non-significant trends towards poorer performance compared to those without aura on motion tasks in some studies (e.g. Antal et al., 2005), but not always (McKendrick et al., 2006; Tibber et al., 2014). Additionally, there is increased perception of illusory motion, the motion-after-effect, in those with migraine compared to controls (Shepherd, 2001; Shepherd, 2006; Shepherd and Joly-Mascheroni, 2017), and there is no difference in the motion after-effect between MA and MO groups (Shepherd, 2001). Importantly, the duration of the motion after-effect was associated with visual triggers, photophobia, and frequency of headaches (Shepherd and Joly-Mascheroni, 2017). Differences in visual processing of motion is important as this could result in increased susceptibility to illusory motion high contrast gratings. Indeed, there is some evidence to support this: those with migraine report increased visual discomfort (including shimmering and scintillating effects) in high-contrast gratings in comparison to control groups (Marcus and Soso, 1989).

As well as visual processing differences, migraine is also associated with differences in multisensory integration (Schwedt et al., 2013; O'Hare, 2017). In particular, the visual and vestibular systems are closely linked, and a mismatch between the visual-vestibular input can lead to the experience of vertigo (Brandt, 2013). Vestibular disorders seem relatively common in migraine: those with migraine can experience vertigo (Bertholon et al., 2006), and there is a sub-classification of individuals with “migrainous vertigo” (von Brevem et al., 2004). There is also evidence of vestibular impairment in around 1/3 of individuals who are not diagnosed as having migraine-with-vertigo (Boldingh et al., 2013), and, importantly, visual stimulation can elicit motion sickness more easily in migraine sufferers compared to control groups (Drummond and Granston, 2004).

Differences in eye movements are associated with postural sway. Nystagmus eye movements are characteristic of migrainous vertigo (Phillips et al., 2010). Differences in eye-movements related to motion processing has been shown in those with migrainous vertigo, as well as MA, compared to control groups (Rogalinski and Rambold, 2017). In addition, the optokinetic effect is related to postural sway (Blanks et al., 1996), therefore this could be a potential difference for the mechanism in migraine. Alternatively, there are potential neurological mechanisms for differences in motion processing in migraine - there is increased cortical thickness in areas MT+ and V3A in those with migraine compared to controls (Granziera et al., 2006). These areas are both strongly associated with motion processing, and also with the processing of head movements (Goosens et al., 2006; Arnoldussen et al., 2011; Fisher et al., 2012; Arnoldussen et al., 2013).

Imaizumi et al., (2015) used a stabilometer to show that that postural sway is greater in migraine sufferers with eyes closed, compared to eyes open: this is increased on viewing the "rotating snakes illusion", which elicits strong illusory motion in the observer. However, there was also an increase in postural sway and visual discomfort, reported from the control condition of a stationary version of the stimulus compared to a plain grey screen. This might therefore indicate that there are residual effects from the pattern that were not completely removed. In order to investigate this more systematically in our experiments, riloid stimuli are more controlled, and only line waviness and spatial frequency will be manipulated.

The aim of this experiment is to establish the most important spatial factors for eliciting head movements in those with and without migraine, using "riloid" stimuli. Riloid stimuli have been used to investigate eye movements in those with migraine previously (Zanker et al, 2005). Postural sway is influenced by head direction (Berensci et al., 2005). Head movements might be indicative of postural sway movements, and instability being transferred from the head through to the rest of the body. Spatial frequency and line waviness will be systematically varied to assess their impact on head movements. In particular, there is an "n"shaped relationship between discomfort and spatial frequency. The maximum discomfort judgements for striped stimuli have been found to be in the range 2-4 cycles/degree (Wilkins et al., 1984). The spatial frequency tuning for discomfort judgements is also seen in filtered noise patterns (Fernandez and Wilkins, 2008); however the tuning peaks at a lower frequency (1.5 cycles/degree) compared to stripes patterns (O'Hare and Hibbard, 2011). Therefore, it is expected that there will be an “n” shaped relationship between magnitude of head movements and spatial frequency, with maximum head movement on viewing the midrange stimulus. It is predicted that the migraine group will show increased head movements compared to the control group on viewing stimuli that elicit illusory motion.

Materials and Methods

Apparatus

An ASUS computer with Intel i5-6500 core processor, 16GB RAM and a dedicated NVidia graphics card, running 64-bit Windows 10 was used to control the headset. A Vive headset (HTC Corporation, 2011-2017) was used to display the stimuli, using an OLED display with a resolution of 2160 x 1200 pixels and 90Hz refresh rate. There are two reasons for this choice of platform: the first is to enable control of the appearance of the environment, in order to remove these potentially stabilising effects (Guitton et al., 1986). The second is to enable the direct measurement of head movements. In addition to an accelerometer and gyroscope, the HTC Vive uses two "lighthouses" to estimate the position of the headset in space, and to give measurements of the x (medio-lateral plane), y (elevation) and z (antero-posterior plane) co-ordinates (of the head) at a fast sampling rate. This has the advantage of direct measurement, rather than estimating head motion from video recordings, for example. Stimuli were displayed using 64-bit Unity 5.61f1 (Unity Technologies, San Francisco, USA), using the SteamVR platform. The simulated environment comprised a box-shaped room with black floor, walls, and ceiling. The riloid patterns were displayed on a virtual wall panel at a display distance of 2.3 m from the observer.

An adapted version of the Pattern Glare Test (Wilkins and Evans, 2001) was used to record subjective responses during stimulus presentation. The original Pattern Glare Test records binary responses to questions regarding illusions of motion, colour and shape that may be perceived on viewing gratings. Three gratings are used in the original test, low, mid-range and high spatial frequency stimuli. These correspond to approximately 0.5, 3, and 12 cycles per degree when the test pattern is at a viewing distance of 40cm. For use in the current study, the questions were modified into a (1-10) Likert rating scale, gathering richer data compared to a binary response. Some of the questions were omitted, e.g. blur of the stimulus, as sine-waves, rather than square-waves, were used in the current study. Questions and responses were given verbally. The question set used can be seen in Table 1.

****************************Table 1 here ***************************

Observers

All experimental procedures adhered to the Declaration of Helsinki (2013) and were scrutinised by the University of Lincoln School of Psychology ethics committee. 41 observers took part in the original study, all with normal, or corrected-to-normal vision, established by using the FrACT Test (Bach, 1996, 2007). Migraine was defined as those meeting the International Headache Society diagnostic criteria (2013). In total, 15 individuals with migraine were included. A table of migraine characteristics can be seen in Table 2. Controls were defined as those experiencing no headaches on a regular basis, three observers recruited for the control group were excluded due to experiencing headaches too frequently. The remaining 13 controls (6 male) had a mean age of 26.77 (SD = 7.53) compared to a mean age of 29.27 (SD = 11.74) for the migraine group.

****************************table 2 here **************************

Stimuli

Stimuli were nine riloid patterns, created using MATLAB version 2015b (Mathworks, Natick, USA). These were originally used in the work by Zanker and colleagues (Zanker et al., 2003; Zanker et al., 2004; Zanker et al., 2010), see equation 1.

$$I(x,y) = 0.5\big(1 + \sin\big[2\,\Pi\,\big(x - \Phi\,(y)\big)\big]\big)$$

Where:

$$\Phi(y) = A \sin\left(2\,\Pi\,\frac{y}{\mu}\right)$$

Where: $I_{(x,y)}$ defines luminance as a function of the horizontal *(x)* and vertical position *(y)*, resulting in a sine wave of frequency *f*, which varied between approximately 6, 48, and 192 cycles/image, with phase modulated as $\Phi_{(y)}$, amplitude *A* was 1, and wavelength μ was 100, 400 and 10^{20} pixels, resulting in 10, 2 and 0 (straight) cycles/image. Spatial frequencies in the display corresponded to 0.16, 1.25 and 5.00 cycles/degree. Images were saved as 1024 x 1024 pixel JPEG images. A modified version of the Pattern Glare Test (Wilkins and Evans, 2001) was used to record subjective responses from the observer. The experimenter asked the questions and the observer answered verbally, the questions did not appear on the display itself.

Procedure

Participants stood in the centre of the experimental area wearing the headset. The experimental area was defined by the lighthouses at each corner. They were allowed time to adjust the virtual reality environment. During the adjustment stage, the environment was a room with furniture set to appear as a living space, the scene included a window looking out over a mountain scene. This was not the same as the experiment environment, which consisted of a totally black space (black skybox), to limit peripheral cues to location in space. During the experiment, participants were asked to keep as still as possible and not to make head movements during the display of the stimuli. There was no fixation point displayed during stimulus presentation, and the task was free viewing conditions. The start screen was a white front screen in a black skybox, with black text saying "Press the trigger to start". Each trial was initiated by pressing the trigger button on the controller. The riloid was displayed for 60 seconds. During this time the experimenter verbally asked the participant questions from the modified Pattern Glare Test. Participants reported their responses verbally. After the display time the white screen was presented again, with a pause until the individual initiated the next trial. Riloids were presented in random order, randomised anew for each observer. Data from the x, y, and z co-ordinates were sampled at 50Hz.

Analysis

Data from x (medio-lateral), y (elevation), and z (antero-posterior) positions of the headset were recorded for each observer, and these time series were read into MATLAB for analysis. Individuals with outlying responses were excluded from analysis, in total 6 individuals. Outlying responses were calculated as follows: responses from all observers were pooled into a single vector for the medio-lateral displacement direction (x), and the mean and the standard deviation of this vector was calculated. Individuals with responses exceeding 3.5 times the standard deviation from the mean of this vector were classed as outliers and excluded. Three separate measures were taken to estimate the movement of the observer whilst viewing the riloid stimuli. In the first measure, the maximum displacement in the lateral directions with respect to the observer (following the convention of medio-lateral as x and antero-posterior as z) was calculated, and the hypotenuse was used as the maximum displacement value for each observer, thus a single figure to characterise a proxy for the maximum displacement area. Sway area has been used in previous research, but there are different definitions for calculation (e.g. Gouwanda et al., 2014; Tarantolaa et al., 1997; Gangloff and Perrin, 2002), therefore a simple metric was chosen as a proxy in the current study. Figure 2 shows the data from one observer, shown as medio-lateral (x) and antero-posterior (z) positions in space, from a top-down view. In the second analysis, following (Latash et al., 2003), the RMS of the movement was calculated. First the data were first filtered using a 4^{th} order Butterworth filter, with a 10Hz cut-off. The first second was removed to reduce the effect of artefacts from the filter, leaving 59 seconds of data per condition. The RMS of the total path in the medio-lateral direction, and in the antero-posterior direction was estimated using the inbuilt MATLAB function. In the final analysis, the overall velocity in the medio-lateral, and the velocity in the antero-posterior direction was estimated by normalising the total path length over time (59 seconds). Data from additional observers can be seen in the supplementary information.

******************************figure 2 here ***************************

Statistical analysis was conducted using the programme R (R Core Team, 2013), using packages "afex" (Singmann et al., 2015), and "lsmeans" (Lenth et al., 2016). Data were subjected to a 2 (group, migraine or control) x 3 (spatial frequency) x 3 (line waviness) mixed ANOVA, including observer as a random variable. A Greenhouse Geissler method was used to adjust the degrees of freedom where the assumption of sphericity was violated.

Results

Figure 3 shows maximum displacement against spatial frequency for the migraine and control group. Results were averaged over line waviness for the figure. A table of means and standard deviations can be seen in Table 3. Results of the 2 x 3 x 3 ANOVA showed a significant main effect of spatial frequency only ($F(1.77,42.59) = 3.88$, $p < 0.05$, $\eta^2_G = 0.03$). Post-hoc Tukey's tests showed there to be a significant difference between the low and midrange spatial frequencies ($p < 0.05$), but not between the low and high ($p = 0.217$) of the midrange and high spatial frequencies ($p = 0.539$). There was no effect of line waviness ($F(1.81,43.59) = 0.21$, $p = 0.79$, $\eta^2_G = 0.002$), or migraine ($F(1,24) = 0.08$, $p = 0.78$, $\eta^2_G = 0.0003$). There were no statistically significant interaction effects (migraine and spatial frequency ($F(1.77,42.59) = 1.89$, $p = 0.17$, $\eta^2_G = 0.01$); migraine and line waviness ($F(1.81,43.43) = 0.02$, $p = 0.97$, $\eta^2_G = 0.0002$); spatial frequency and line waviness ($F(3.36,80.70) = 0.82$, $p = 0.50$, $\eta^2_G = 0.02$); migraine, spatial frequency and line waviness ($F(3.36,80.70) = 0.63$, $p = 0.61$, $\eta^2_G = 0.01$)).

****************************figure3 here ******************************

*************************table 3**************************

RMS displacement

RMS in the medio-lateral direction

Figure 4A shows the RMS displacement in the medio-lateral direction against spatial frequency for both the migraine and control groups, again averaged over line waviness. Table 4 shows the means and standard deviations. There was a main effect of spatial frequency ($F(1.75,40.31) = 8.19$, $p = 0.002$, $\eta^2_G = 0.05$). Post-hoc Tukey tests showed there was a significant difference between the low and midrange spatial frequencies ($p = 0.0008$), and between the low and high spatial frequencies ($p = 0.0215$), but not between the midrange and high spatial frequencies ($p = 0.4775$). There was no main effect of migraine ($F(1,23) = 0.07$, $p = 0.79$, $\eta^2_G = 0.0002$). There was no main effect of line waviness ($F(1.86,42.85) = 0.28$, $p = 0.74$, $\eta^2_G = 0.004$). There was no interaction between migraine and spatial frequency ($F(1.75,40.31) = 0.66$, $p = 0.50$, $\eta^2_G = 0.004$), no interaction between migraine and line waviness ($F(1.86,42.85) = 0.08$, $p = 0.91$, $\eta^2_G = 0.001$). There was no interaction between spatial frequency and line waviness ($F(3.09,71.14) = 0.75$, $p = 0.53$, $\eta^2_G = 0.02$). There was no three-way interaction between migraine, spatial frequency and line waviness ($F(3.09,71.14) = 0.47$, $p = 0.71$, $\eta^2_G = 0.010$).

*********************************figure 4 here ****************************

***********************************table 4 here***************************

RMS in the antero-posterior direction

Figure 4B shows the RMS displacement against spatial frequency in the antero-posterior direction for migraine and control groups, averaged over line waviness. Table 4 shows the means and standard deviations. There was no effect of migraine ($F(1,23) = 0.00$, $p > 0.99$, $\eta^2_G < 0.0001$), no effect of spatial frequency ($F(1.55,35.75) = 1.10$, $p = 0.33$, $\eta^2_G = 0.008$), and no effect of line waviness ($F(1.97,45.34) = 0.00$, $p > 0.99$, $\eta^2_G < 0.0001$). There is no interaction between migraine and spatial frequency ($F(1.55,35.75) = 0.01$, $p = 0.97$, $\eta^2_G < 0.0001$), between migraine and line waviness ($F(1.97,45.34) = 0.01$, $p = 0.99$, $\eta^2_G = 0.0002$), or between spatial frequency and line waviness ($F(3.76,86.48) = 0.11$, $p = 0.97$, $\eta^2_G = 0.002$). There is no three-way interaction between migraine, spatial frequency and line waviness ($F(3.76,86.48) = 0.06$, $p = 0.99$, $\eta^2_G = 0.001$).

Velocity

Velocity in the medio-lateral direction

Figure 5A shows the velocity in the medio-lateral direction against spatial frequency for the migraine and control group, averaged over line waviness. Table 5 shows the means and standard deviations. There was a significant effect of spatial frequency ($F(1.73,39.76) = 7.46$, $p = 0.003$, $\eta^2_G = 0.05$). Post-hoc Tukey tests showed there to be a significant difference between the low and midrange spatial frequencies ($p = 0.0015$), and between the low and high spatial frequencies ($p = 0.0241$), but not between the midrange and high spatial frequencies ($p = 0.5768$). There was no main effect of migraine ($F(1,23) = 0.07$, $p = 0.80$, $\eta^2_G = 0.0002$), and no effect of line waviness ($F(1.86,42.73) = 0.34$, $p = 0.70$, η^2_G 0.004). There was no interaction between migraine and spatial frequency ($F(1.73,39.76) = 0.65$, $p = 0.51$, $\eta^2_G = 0.004$), no interaction between migraine and line waviness ($F(1.86,42.73) = 0.10$, $p = 0.90$, $\eta^2_G = 0.001$), and no interaction between spatial frequency and line waviness ($F(2.95,67.90) = 0.74$, $p = 0.53$, $\eta^2_G = 0.02$). There was no three-way interaction between migraine, spatial frequency and line waviness ($F(2.95,67.90) = 0.46$, $p = 0.71$, $\eta^2_G = 0.01$).

*********************************figure 5 here **************************

***************************table 5 here ****************************

Velocity in the antero-posterior direction

Figure 5B shows the velocity in the antero-posterior direction against spatial frequency for the migraine and control group, averaged over line waviness. Table 5 shows the means and standard deviations. There was no significant main effect of migraine ($F(1,23) = 0.00$, $p = 0.99$, $\eta^2_G < 0.0001$). There was no main effect of spatial frequency ($F(1.57,36.21) = 1.12$, $p = 0.32$, $\eta^2_G = 0.008$), or line waviness ($F(1.95,45.27) = 0.02$, $p = 0.98$, $\eta^2_G = 0.0002$). There is no interaction between migraine and spatial frequency ($F(1.57,36.21) = 0.03$, $p = 0.94$, $\eta^2_G = 0.0002$), there is no interaction between migraine and line waviness ($F(1.97,45.27) = 0.01$, $p = 0.99$, $\eta^2_G = 0.0002$), and no interaction between spatial frequency and line waviness ($F(3.74,86.08) = 0.11$, $p = 0.97$, $\eta^2_G = 0.002$). There is no three-way interaction between migraine, spatial frequency and line waviness ($F(3.74,86.08) = 0.05$, $p = 0.99$, $\eta^2_G = 0.001$).

Subjective judgements

Illusory motion

Figure 6A shows average ratings for perceived illusory motion against spatial frequency, averaged over line waviness. Figure 6B shows average ratings for perceived illusory motion against line waviness, averaged over spatial frequency. Means and standard deviations can be seen in Table 6. Analysis of variance showed there to be a statistically significant effect of spatial frequency ($F(1.78,42.68) = 8.93$, $p = 0.0009$, $\eta^2_G = 0.06$) and of line waviness ($F(1.53,36.74) = 4.66$, $p = 0.02$, $\eta^2_G = 0.04$) on judgements of illusory motion from riloid stimuli. Post-hoc Tukey tests showed there to be a significant difference between the low and midrange spatial frequency stripes ($p = 0.0013$), and between the low and high spatial frequencies ($p = 0.0026$), but not between the midrange and high spatial frequency stripes ($p = 0.966$). There was a significant difference between the straight and waviest lines ($p = 0.0157$), but not between the straight and medium wavy lines ($p = 0.06$) or between the medium and wavy lines ($p = 0.830$). There was no effect of migraine group ($F(1,24) = 1.45$, $p = 0.24$, $\eta^2_G = 0.01$). There was no interaction between spatial frequency and migraine ($F(1.78,42.68) = 1.52$, $p = 0.23$, $\eta^2_G = 0.04$), no interaction between line waviness and migraine ($F(1.53, 36.74) = 0.50$, $p = 0.56$, $\eta^2_G = 0.004$), and no interaction between spatial frequency and line waviness ($F(2.58,62.03) = 1.97$, $p = 0.14$, $\eta^2_G = 0.03$). There was no three-way interaction between migraine, spatial frequency and line waviness ($F(2.58,62.03) = 1.71$, $p = 0.18$, $\eta^2_G = 0.03$).

****************************figure 6 here *****************************

********************************table 6 here ********************************

A linear mixed effect model (Bates et al., 2015) was created to estimate the relationship between perceived illusory motion ratings and head movements. Perceived illusory motion ratings were used as a fixed effect, and observer as a random effect to predict maximum displacement. There was a significant relationship found ($\chi^2_{(1)} = 3.9767$, p = 0.04613). Perceived illusory motion perception increased head movements by 2.195mm ± 1.096mm (standard error). There was no relationship between any of the other subjective measures: perceived flicker ($\chi^2_{(1)} = 0.0047$, p = 0.9456), perceived illusory colours ($\chi^2_{(1)} = 0.3475$, p = 0.5555), perceived fading ($\chi^2_{(1)} = 2.6782$, p = 0.1017) or perceived shadowy shapes ($\chi^2_{(1)} = 0.0406$, p = 0.8402) with maximum displacement head movements.

A linear mixed effect model was created to estimate the relationship between perceived illusory motion ratings and RMS head movements in the medio-lateral direction. There was a significant relationship found in the medio-lateral direction ($\chi^2_{(1)} = 4.1346$, p = 0.04202). Perceived illusory motion increased head movements by 1.212mm ± 0.5934mm (standard error). There was no relationship with flicker ($\chi^2_{(1)} = 2.1794$, p = 0.1399) or with perceived illusory colours ($\chi^2_{(1)} = 2.0608$, p = 0.1511). There was a significant relationship between medio-lateral RMS head movements and perceptions of fading of the lines ($\chi^2_{(1)} = 4.1874$, p = 0.0407). Perception that the lines appeared to fade decreased medio-lateral head movements by 1.004mm, ± 0.4882mm (standard error). There was also a relationship between perception of illusory shadowy shapes and medio-lateral head movements ($\chi^2_{(1)} = 7.398$, p = 0.0065), with the perception of illusory shadowy shapes increasing medio-lateral head movements by 1.879mm ± 0.6852mm (standard error).

For RMS head movement in the antero-posterior direction, there was no relationship with perceived illusory motion ($\chi^2_{(1)} = 0.1915$, p = 0.6617), with perception of flicker ($\chi^2_{(1)} = 0.0694$, p = 0.7922), perceived illusory colours ($\chi^2_{(1)}$ = 0.6483, p = 0.4207), perception of fading ($\chi^2_{(1)}$ = 0.3766, p = 0.5394) or perception of shadowy shapes ($\chi^2_{(1)}$ = 2.0697, p = 0.1503).

A linear mixed effect model was used to investigate the relationship between velocity in the medio-lateral direction and subjective judgements. There was a relationship between perceived illusory motion and medio-lateral velocity ($\chi^2_{(1)}$ = 4.3699, p = 0.03658), with medio-lateral head movements increasing by 0.05819m/s ± 0.02770m/s (standard error). There was no relationship between medio-lateral head velocity and perceived flicker ($\chi^2_{(1)}$ = 2.4901, p = 0.1146), or perceived illusory colours ($\chi^2_{(1)}$ = 2.7185, p = 0.09919). There was a relationship between medio-lateral velocity and perceptions of fading of the lines ($\chi^2_{(1)}$ = 4.4447, p = 0.03501), with a reduction in medio-lateral head movements of 0.04829m/s ± 0.02279m/s (standard error). There was a relationship between medio-lateral velocity and perceived shadowy shapes ($\chi^2_{(1)}$ = 8.8704, p = 0.0028), with medio-lateral velocity increasing by 0.09595m/s ± 0.03190m/s (standard error).

For velocity in the antero-posterior direction, there was no relationship with perceived illusory motion ($\chi^2_{(1)}$ = 0.1743, p = 0.6763), with flicker ($\chi^2_{(1)}$ = 0.0644, p = 0.7996), with perceived illusory colours ($\chi^2_{(1)}$ = 0.599, p = 0.439), with fading ($\chi^2_{(1)}$ = 0.3108, p = 0.5772), or with shadowy shapes ($\chi^2_{(1)}$ = 2.0365, p = 0.1536).

Discussion

An effect of spatial frequency on head movements was found; the midrange spatial frequencies (around 1.25 cycles per degree in this experiment) were capable of systematically inducing increased head movement for both migraine and control groups. Additionally, there was a relationship between reports of illusory motion and head movements in the current observers. This relationship was only seen in the medio-lateral head movements, not in the antero-posterior head movements. There was no effect of line waviness on head movements. There was no evidence of a group difference between migraine and control groups.

Increased head movements from op-art based stimuli could result from increased visual discomfort, which includes illusions of motion, commonly referred to as "shimmering" or "scintillating" patterns elicited by high contrast gratings (Wilkins et al., 1984). The results of this experiment show that increased visual illusions can elicit vestibular motion large enough to be measured using a virtual reality headset. As postural sway is influenced by head movements (Berensci et al., 2005), this might have implications for the design of virtual environments, as an increase in head movements may lead to an increase in disorientation, and postural sway in observers.

The effect of spatial frequency on head movements was found using three different measures, the maximum displacement, the RMS displacement and also the velocity. When the medio-lateral and antero-posterior head movements were analysed separately, it was found that head movements were greater in the antero-posterior direction compared to the medio-lateral direction, in line with findings of greater movement in the antero-posterior direction compared to the medio-lateral direction in quiet standing (e.g. Latash et al., 2003). In addition, the relationship between perceived illusory motion and head movements was only seen for the medio-lateral movements, not the antero-posterior movements. This was true for both measures of RMS and velocity that were split into the separate directions. In addition, head movements in the medio-lateral direction only also show a relationship with perceived shadowy shapes, and apparent fading of the lines. Shadowy shapes are seen in regular patterns, such as the Hermann grid illusion (Hermann, 1870). However, this is unlikely to be the same mechanism as the Hermann grid illusion disappears with sine-wave modulation, which is the case with the riloid patterns (Geier et al., 2008). Interestingly, the perceived fading of the lines has a negative relationship with medio-lateral head movements. It might be that the apparent fading of the stimulus reduces the apparent contrast, resulting in a weaker stimulus and therefore less able to evoke head movement; however, this interpretation is speculative at present as the current study does not provide direct evidence for this possibility. This is a similar direction selectivity as shown by Holten et al., (2014), who also found movement specific to the medio-lateral direction. In the current study, observers were not asked about the direction of the perceived motion. However, as all riloid stimuli were presented in the same orientation, this could explain the direction specificity of the results. Future studies could address this by using patterns that evoke sensations of illusory motion in the antero-posterior direction, i.e. illusions of expansion and contraction.

Eye movements affect postural control (Uchiyama & Demura, 2009); it could therefore be argued that illusions of motion affect the control of the eyes, and this affects head movements, rather than any visual discomfort arising from the illusions. However, illusions of motion from riloid stimuli have not been demonstrated to have an effect on eye movements themselves (Hermens et al., 2012). Alternatively, there are neural accounts for increased discomfort from op-art based visual stimuli. One possibility is that stimuli with statistical properties very different to those of natural images are unable to be efficiently coded by the visual system (Juricevic et al., 2010). As a result, these stimuli might cause excessive responses which are metabolically costly. This possibility has been demonstrated in models of uncomfortable stimuli and artworks (Penacchio et al., 2015; Hibbard and O'Hare, 2015). Also, there is some evidence to support this idea in terms of increased VEP responses to uncomfortable riloid patterns (O'Hare et al., 2015). The "rotating snakes" illusion induces more activity in the medial-temporal areas (specifically, V5) compared to a control stimulus that does not evoke perceptions of illusory motion (Kuriki et al., 2008). Adaptation to perceived illusory motion resulting from the "rotating snakes" illusion is present through additional visual areas, V1, V2, V3A and also V4, under stable fixation conditions, suggesting firstly that there is a network of activation for illusory motion perception, and also the cortical activity is unlikely to be accounted for by eye movements alone (Ashida et al., 2012). However, as neither eye movements nor EEG responses were measured in the current study, it is not possible to draw conclusions about the mechanism at this point.

It was expected that those with migraine would show increased head movements as a result of viewing stimuli that elicits visual discomfort, particularly illusions of motion. This was not found to be the case. However, those with a predisposition to relying on visual information more might be more affected by the illusory effects of the stimuli, rather than those with a diagnosis of migraine. Previous research by Imaizumi et al., (2015) demonstrated a difference between migraine and control groups on postural sway after viewing the rotating snakes illusion. It could be that the rotating snakes elicits a more powerful illusion of motion compared to riloid patterns, and demonstrated the group differences. Alternatively, it could be that Imaizumi et al., (2015) used a stabilometer to measure postural sway, which is different from the head movements measured using the HTC Vive in the current study. HTC Vive has been shown to be reasonably reliable and accurate, except for when tracking is lost, i.e. communication between the headset and the lighthouses is temporarily disrupted, for example when the observer moves around the game area (Niehorster et al., 2017). This is not the case in the current study.

Another difference between the current study and that of previous work is that Imaizumi et al., (2015) calculated the Romberg Ratio in their analysis, which is the ratio of the measurement with eyes closed to eyes open. The Romberg Ratio has been found to be unreliable (Tjernström et al., (2015), and so this was not used in the current study.

Participants answered questions regarding the stimuli verbally during the stimulus display time, in order to obtain an instantaneous subjective measure without the need to remember answers. However, answering subjective questions placed a cognitive load on the observer, and it has been shown that the difficulty of a cognitive task reduces postural sway (Swan et al., 2007). It is therefore possible that the observed lack of inter-group difference in postural sway (compared to previous work by Imaizumi et al., 2015) could be due to the introduction of a cognitive task.

Individuals experiencing migraine with visual aura (MA) tend to show poorer performance on visual tasks compared to those experiencing migraine without aura, for example Shepherd (2000) reports trends towards greater number of illusions on the Pattern Glare Test and also poorer contrast sensitivity in MA compared to those without aura; however the difference between MA and other migraine was not significant. Additionally, some authors have shown no difference between those with and without aura in tasks involving the perception of motion stimuli (e.g. Tibber et al., 2014). In the current study, there were only three individuals with a diagnosis of MA, and so it might be argued that the lack of effect is due to including both MA and those without aura in the group. However, in the study by Imaizumi et al., (2015) only one of the participants experienced MA, yet these authors demonstrated effects of perceived illusory motion on postural sway.

The behavioural ratings showed effects of spatial frequency for perceived illusory motion, flicker, and illusory colours. The midrange and thin lines causes the greatest effect, rather than the wider lines. The midrange lines are within the spatial frequencies previously shown to cause discomfort from filtered noise patterns (O'Hare and Hibbard, 2011). The higher spatial frequencies are slightly above the range previously shown to cause most discomfort from striped patterns (Wilkins et al., 1984). There was no effect of group on perceptions of illusory motion from riloid stimuli. This is unexpected as those with migraine would be expected to show increased discomfort from striped stimuli (Wilkins et al., 1984). However there is also wide variation in subjective discomfort in normal populations also (Conlon et al., 1999). In visual search tasks, it has been found that susceptibility to visual discomfort, not migraine diagnosis, was a predictor of performance (Conlon and Humphreys, 2001). This might account for the null effect of migraine group on perceived motion, and also on postural sway. As there were effects of some aspects of visual discomfort, but not others, then it might be worthwhile in future research to separate visual discomfort into its component attributes, to allow more specific conclusions.

Conclusion

Spatial frequency of riloid stimuli increased head movements and perceived illusory motion in observers. This would suggest that visual discomfort, possibly from either eye movements or excessive neural responses, is related to increased head movements. There was no increase in head movements or perceived illusory motion in migraine compared to control groups. This could be due to variation in visual discomfort in the general population in addition to those with migraine. However, there was increased visual discomfort in terms increased colour illusions from riloid stimuli in the migraine compared to the control group, in line with previous research. This might suggest that future research into visual discomfort might benefit from considering the different components separately.

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Figure Captions

Figure 1: Schematic riloid stimuli. Left to right is increasing spatial frequency (λ), top to bottom is increasing μ (decreasing line waviness).

Figure 2: Data from one observer, showing head displacement for each of the riloid stimuli. The mediolateral (x) position is plotted against the antero-posterior displacement (z). Each point represent co-ordinates for a head position at a different time points. This shows a top-down view of the path of head movements for one observer. Each stimulus is represented by a different colour. Stimulus 1 = low spatial frequency, waviest lines. 2 = mid-range spatial frequency, waviest lines. 3 = high spatial frequency, waviest lines. 4 =low spatial frequency, medium wavy lines. 5 = midrange spatial frequency, medium wavy lines. 6 = high spatial frequency, medium wavy lines. 7 = low spatial frequency, straight lines. 8 = midrange spatial frequency, straight lines. 9 = high spatial frequency, straight lines.

Figure 3: Average maximum displacement (in metres) for the three spatial frequency stimuli, averaged over line waviness. Narrower boxes indicate the migraine group, wider boxes indicate the control group. Notches indicate the median, box boundaries show the 25th and 75th percentiles, whiskers indicate the range, outliers are marked by individual points. Red = low spatial frequency, blue = medium spatial frequency, black = high spatial frequency stimuli.

Figure 4: Average RMS displacement (in metres) for the three spatial frequency stimuli, averaged over line waviness for the migraine and control groups. Thinner boxes indicate the migraine group, wider boxes indicate the control group. A: RMS displacement in the medio-lateral direction. B: RMS displacement in the antero-posterior direction. Notches indicate the median, box boundaries show the 25th and 75th percentiles, whiskers indicate the range, outliers are marked by individual points. Red = low spatial frequency, blue = medium spatial frequency, black = high spatial frequency stimuli.

Figure 5: Average velocity (m/s) for three spatial frequency stimuli, averaged over line waviness, for the migraine and control groups. Migraine group indicated by the thinner boxes, control group by the wider boxes. A: Velocity in the medio-ventral direction. B: Velocity in the antero-posterior direction. Notches indicate the median, box boundaries show the 25th and 75th percentiles, whiskers indicate the ranges, outliers marked by individual points. Red = low spatial frequency, blur = medium spatial frequency, black = high spatial frequency stimuli.

Figure 5: Ratings for perceived illusory motion. Migraine indicated by thinner boxes, controls by the wider boxes. A: perceived illusory motion for three spatial frequencies, averaged over line waviness. Red = low, blue = mid, black = high spatial frequency stimuli. B: perceived illusory motion for three levels of line waviness, averaged over spatial frequency. Red = wavy, blue = medium wavy, black = straight lines. Notches indicate the median, box boundaries show the 25th and 75th percentiles, whiskers indicate the range, outliers are marked by individual points.